TYPES OF ORE DEPOSITS

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EDITED BY

H. FOSTER BAIN

With Chapters by

H. Foster Bain
E. R. Buckley
S. F. Emmons
W. H. Emmons
F. H. Hatch
Oscar H. Hershey
J. D. Irving
J. F. Kemp
A. C. Lane
C. K. Leith
R. A. F. Penrose, Jr.
T. A. Rickard
C. H. Smyth, Jr.

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PREFACE.

This book is designed to present an accurate account of the present state of opinion regarding the genesis of ores. The individual chapters have been written, each by a different engineer and each by one particularly familiar with the type of deposit that he describes. Each author is responsible only for what he has written. Probably no one would accept entire the interpretations of all the others. Each has given the reason for the faith that is within him and submits the matter on his own statement of the case, to the judgment of his professional fellows. It has been the editor's pleasant task merely to bring the material together and secure its presentation in one volume. He has had neither inclination nor authority to make other than those minor changes in the manuscripts submitted necessary to secure a certain uniformity of typographical style. The material in the various chapters is not new except in form. In certain cases, by arrangement, the papers have been previously published and are reproduced by permission. Mr. Lane's discussion of native copper deposits and Mr. Irving's of replacement orebodies, were read before the Canadian Mining Institute last winter. Mr. Hershey's paper on the Treadwell deposits, that of Mr. S. F. Emmons on Cobalt, and of Mr. W. H. Emmons on outcrops are reproduced from the *Mining and Scientific Press*. The remaining chapters were written for this book though material previously printed in the Transactions of the American Institute of Mining Engineers, the reports of the United States and the State Geological Surveys, and in other publications, has been freely used by the authors. The admirable general discussion of the causes of oreshoots that closes the volume was printed first in *Economic Geology*. To the periodicals and institutions mentioned, and to the *Journal of Geology*, the editor is under obligations for the loan of certain of the illustrations.

H. Foster Bain.

San Francisco, December 1, 1911.

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INTRODUCTION.

By H. Foster Bain.

The science of ore deposits has become so broad that no one man can hope to compass the field. Attempts to do so lead but to false perspective. There is value in having material collated, summarized, and tested by a single point of view, but there is also danger. The map in an ordinary railway folder illustrates this point. On it everything has been reduced to a single viewpoint. It is, therefore, admirably clear; all unessentials (and many essentials) are omitted. Examining it leads to deep conviction that the particular railway issuing the folder follows the shortest and most direct route between terminals. In order to prove this point difficult mountains are smoothed away, rivers are made to flow large or small at will, States are warped, and cities and towns are ruthlessly plucked from their sites as determined by nature or real estate syndicates; the whole web of relations of point to point is distorted. In much the same manner he who has a theory of ore genesis and attempts to apply it to the whole field, quite unconsciously magnifies certain relations at the expense of others. Mountains of difficulties are smoothed away, underground waters are made to flow up or down at will, the crust of the earth is warped now in and now out, well laid out and thriving individual studies of particular types of deposits are summarily seized and made to support the main line of argument; the whole web of fact to fact is thrown out of joint. What the resulting treatise gains in unity and clearness, it too often more than loses in accuracy.

In this book the attempt is made to get away from these difficulties without, it is hoped, becoming inextricably tangled in others that are greater. The work has been made up on the plan of having a series of typical deposits described, in each case by the engineer especially familiar with the type. A plain statement of facts, followed by the particular author's interpretation of the facts and of the relations of the particular type of deposits to ore genesis in general, was requested from each contributor. In a few cases, a phase of ore deposition rather than a type of deposit has been discussed. The plan was evolved some years ago and the support of a number of economic geologists secured. In carrying it out several changes have been necessary. Various members of the original group, losing interest in the project, or finding the pressure of other duties too great to permit them to contribute their parts, have dropped out and others have taken their place. In still other cases promised contributions have failed to materialize and the Editor has regretfully closed the forms without them.

It has been no part of the plan that all types of deposits should be described or that the book should be complete. It was felt much more important that it should be representative. No unity, other than in form, has been attempted. As a matter of fact competent observers differ greatly in their interpretation of even the generally known facts regarding ore deposits, and any accurate presentation of the present state of the science must reflect that diversity of opinion. Probably somewhat different explanations would be offered for each of the types here described, by each of the men contributing to this book. The volume therefore represents in part the modern diversity of interpretation as well as the actual diversity of types in ore deposits.

The very early notion that many of the bedded ore deposits, at least, were formed like other sedimentary rocks, has been frequently pushed too far. Probably no one familiar with the facts now doubts that many orebodies having all the external appearances of true bedded deposits have been formed in reality by replacement of pre-existing beds. Mr. Irving presents illustrations of such cases in this book, and so fully describes them that repetition is unnecessary. There remain, however, other bedded deposits which repeated investigation tends to show were formed by much the same processes as result in deposition of limestones and other sedimentary rocks. Of these, among metallic ore deposits, the Clinton iron ores are probably best known and most truly representative. Mr. Smyth's careful studies of these ores were first published some years since. There has been abundant time and opportunity for refutation of any of his arguments that were unsound, but each year has confirmed the results of his first field and microscopic studies. In the description of the type which he has contributed to this volume these later observations and arguments are incorporated. A careful reading of the chapter will, I believe, lead to the conviction that the Clinton type is a true one, and one that in any discussion of ore genesis involving more than the narrow field of gold-silver veins, must be considered quantitatively important. Deposits of this type, syngenetic ores, are admittedly less numerous than those in which the ore is of later age than the enclosing rock. It is but natural that attention has been concentrated mainly on the latter.

The first great American economic geologist was J. D. Whitney, and the bulk of his early work was in the Mississippi Valley. It was inevitable, therefore, that almost from the time that ore deposits began to be scientifically studied in the United States, there has been a strong trend of opinion favorable to the group of hypotheses of genesis of which Sandberger's doctrine of lateral secretion was the European prototype. That ore deposits in general represented concentrations of material originally widely disseminated, and that in general, they were concentrated from rocks in the vicinity of the ore occurrence, has long been strongly held on both sides of the Atlantic. The various phases through which this group of hypotheses passed have been admirably traced by S. F. Emmons[1] in one of those charming addresses in which he summarized the results of wide reading and long continued personal study of the science to which he devoted his life. He has also shown that parallel with it there was developing from the old and crude notions of veins as consisting of molten eruptive material, something corresponding to the modern notion of gold-quartz veins as after effects of intrusions of igneous rocks. As early as 1865, according to Emmons, from whom I quote, Ferdinand von Richthofen, in his report to the Sutro Tunnel Co., gave shape to this doctrine and listed the following as characteristics of 'true fissure' veins: (1) that they cut rocks of different kinds; (2) that they extend to an indefinite depth; (3) that they show evidence of dynamic action; (4) that they are ordinarily connected with the ejection of some eruptive rock; (5) that they are filled mainly from below and essentially by chemical action. Von Richthofen then says that various agencies have been advocated by different persons as the sole origin of veins, namely, infiltration from above, from the walls, from thermal action; but experience has shown that all these have been more or less simultaneously active in the filling of every true fissure vein. Thermal spring action would not explain the decomposition of the country for two miles to the east of the Comstock Lode; hence, the filling of the fissure must be regarded as the result of solfataric action, a solfatara being a vent for the violent emission of steam at or near an active volcano. Every solfatara passes through two stages: (1) one in which steam is accompanied by gaseous combinations of fluorine

[1] See Jour. Canadian Min. Inst, 1909; see also *Mining and Scientific Press*, September 18, 1909; *Ibid*, May 21, 1910.

and chlorine; (2) by those of sulphur. A later phase, marked by the emission of carbonic acid gas, is no longer solfataric. In the Comstock silica was deposited in the first stage, and the fissure being opened again, the metallic minerals were then introduced as the second stage. As for the source of the water which furnished the steam and acted as a solvent, he says the ocean was too far away, but the waters from the Great Basin, which had a similar composition, penetrated to the heated region, thus furnishing the same source for fluorine and chlorine that they are supposed to have in active solfataras. "As for the source of the mineral substances," he says, "we have to look for the action of these elements on the surrounding rocks."

Another Western investigator who early developed ideas about ore deposits that were essentially modern in many particulars, was Joseph LeConte, the well known professor of geology in the University of California. In 1871 he published an article[2] in which he announced his belief that veins were due to (*a*) deposition from solution; (*b*) that the solutions were hot; and (*c*) that they were alkaline. In his text-book,[3] published in 1878, he discriminated: (*a*) veins of segregation, which contain no open spaces and have been formed by concretionary action; (*b*) veins of infiltration, which are small veins or cracks, filled by lateral secretion from their walls; (*c*) fissure veins, which are great fissures produced by movements of the earth's crust and later filled by mineral matter brought up by hot waters. He did not commit himself as to the source of the waters forming veins. For the derivation of the mineral matter, he was practically a lateral secretionist, for, though he only appealed explicitly to lateral secretion in the case of small veins or those of infiltration, he says: "The great fissure veins derive their contents in each part from *all* the strata to great depths and especially from the deeper strata"—which was the lateral secretion theory in its broader sense as subsequently maintained by economic geologists in America. After he had made his later studies (1881) on the Sulphur Bank of California,[4] where cinnabar and quartz are found forming as crust around brecciated fragments of country rock, he ascribed the filling of veins more definitely to the action of thermal springs, charged with alkaline sulphides, with an excess of sulphuretted hydrogen and carbonic acid. Apropos of the question under general discussion at that time as to the

[2] *Mining and Scientific Press*, 1871, p. 23.
[3] 'Elements of Geology,' Appleton & Co., 1878.
[4] *Amer. Jour. Sci.*, Vol. XXIV, July 1882, and Vol. XXV, June and July 1883.

genetic dependence of metalliferous deposits on igneous rocks, he concluded from these observations that the igneous rocks supplied the heat for the rising waters, but not the materials they carried, since in the Yellowstone Park, where thermal waters come directly from the igneous rocks, there are no metalliferous deposits; whereas at Sulphur Bank the hot waters come up through sandstones, and igneous rocks occur only at the surface. The idea that there were 'true fissure veins' and that they became increasingly rich in depth, obtained wide foothold in the latter half of the nineteenth century. Indeed engineers in that period were usually content to express the opinion that the particular deposit under examination was a 'true fissure vein.' All that was desirable in connection with an ore deposit was supposed to follow inevitably.

The growing notion that veins derived their material from great depth, rather than from surrounding rocks, culminated in the address delivered at Chicago in 1893 by F. Posepny. This was printed, with the resulting discussion, in the well known special volume of the American Institute of Mining Engineers.[5] Posepny's paper produced a profound impression. He presented the strongest and most definite arguments in favor of the 'ascensionist' theory and in disproof of the lateral secretion theory as formulated by Sandberger. While he believed absolutely in the derivation of the metals in veins from a barysphere, he did not discuss the difficulties involved in the inaccessibility of this metal-rich central portion of the earth to descending vadose or meteoric waters. Neither did he, nor his immediate successors in the discussion, suggest any other source for waters circulating in the crust. It was not until several years later that Suess, the great Austrian geologist, established the truth that juvenile waters constitute an important factor in the problem. In 1893, and for more than a decade thereafter, any other sufficient source for ore-forming waters, than meteoric, was not often considered. There was a general assumption, rather than clearly defined belief, that the waters that fell on the surface of the earth penetrated to great depths and returned with the burden of mineral matter that forms the body of veins. Posepny's extreme views as regards derivation of ores from below provoked a natural reaction which in turn culminated in the paper read by C. R. Van Hise at the meeting of the American Institute of Mining Engineers at Washington, D. C., in 1900.[6] This was later revised and republished

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[5] 'Genesis of Ore Deposits,' New York, 1902.

[6] 'Some Principles Controlling the Deposition of Ores,' Trans. Amer. Inst. Min. Eng., Vol. XXX, pp. 27-177.

as chapter XII of his monumental treatise on metamorphism.[7] In the latter, Van Hise states that his main conclusions regarding ore deposits are as follows: (1) Ores deposited by aqueous solutions form the dominant class; (2) the major part of the water performing the work is meteoric; (3) metals for ores deposited by aqueous solutions are derived from rocks within the zone of fracture; (4) solutions which perform the first work in the genesis of ore deposits, the dissolving of metals, are descending; (5) many ores in their first concentration are precipitated by ascending waters. In considering these conclusions the fact must be kept in mind that Van Hise was discussing the whole body of metallic ores and not alone the gold-silver bearing veins that have attracted main attention in the last decade. Thinking of ore genesis as but one of the minor processes of rock formation, and being led into the subject through his studies of the Lake Superior iron ores, his point of view was slightly different from that of those who have written mainly of the ore deposits of the Western States. Fixing first a limit of depth below which open fractures could not exist in the rocks, and relying mainly on meteoric waters because of presumed quantitative inadequacy of others, he showed that the work of concentration of metal into ores must be a function of surface waters acting in the upper part of the crust, and under these conditions that the process of solution must dominate during the downward progress of the waters and that of precipitation during their return. The whole is a wonderfully simple and systematic presentation of a series of complex processes, and it links ore genesis with rock genesis in an extremely satisfactory manner. There is no doubt but that the principles that Van Hise lays down apply exactly in a large number of cases and with but slight modification in still others. The chapters in this volume descriptive of the Lake Superior iron ores, and of the lead and zinc deposits of Wisconsin and of the Ozark region, written by students and fellow-workers of Van Hise, illustrate types of deposits to which his principles apply with but slight modification. In the first, Mr. Leith summarizes present conclusions regarding the great iron-ore deposits that were the especial field of Van Hise's studies. The general agreement between this and the earlier discussions by Van Hise and Leith is evident, but it will be noted that Mr. Leith now emphasizes the relation of the ores to certain peculiar ellipsoidal basalts and suggests that derivation of the ores from them may have been not only through processes

[7] 'Treatise on Metamorphism,' U. S. Geol. Surv., Mon. 47, Washington, 1904.

of weathering, but through direct contribution by juvenile waters. This is significant of the general change of opinion since 1900.

In the description of the flats and pitches of the Wisconsin lead and zinc deposits which follows, I have centred attention mainly on the structural features of the orebodies and their general relations to a normal cycle of erosion and deposition. I have endeavored to make clear that these deposits represent orebodies of first rank that must have originated without any direct relations to igneous rocks or agencies. To the evidence to that effect given in the text, it may now be added that investigations by E. T. Allen and his associates in the geophysical laboratory of the Carnegie Institute at Washington, have shown by direct test that marcasite, an abundant accessory mineral in the Wisconsin deposits, is formed at low temperatures and in acid solutions.[8] This confirms the field evidence that the deposits were formed by meteoric waters near the surface. As to the exact course of the waters and even as to their immediate gathering ground, there is room for difference of opinion. J. D. Whitney, T. C. Chamberlin, C. R. Van Hise, U. S. Grant, and others have described the deposits and outlined somewhat different theories as to their genesis. In the text I have formulated one possible process. G. H. Cox has since outlined another.[9] Perhaps the last word has not yet been said, but all investigators personally familiar with the region, since the early days of Owen and Percival, agree as to the main conclusion—that the lead and zinc ores of the upper Mississippi Valley have been deposited by meteoric waters circulating at shallow depth.

The economically more important and structurally more varied lead and zinc deposits of the Ozark region are described by E. R. Buckley, whose work as Director of the Bureau of Mines and Geology of Missouri, and whose later professional engagements with companies mining in the region, has given him an intimate knowledge of the deposits. In the essentials his conclusions regarding the ores correspond with those of Van Hise, though he modifies the application of the principles in many important particulars. He finds no sufficient ground for belief in a first concentration through wide-reaching artesian waters as had been advocated by Van Hise and Bain.[10] He, however, holds clearly that the ores were formed by meteoric waters circulating through but the outer crust of the

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[8] E. T. Allen. 'Sulphides of Iron and Their Genesis,' *Mining and Scientific Press,* September 30, 1911.

[9] *Economic Geology,* Vol. VI, pp. 427-448.

[10] U. S. Geol. Surv., 22nd Ann. Rept., Pt. II, 1901, pp. 33-227.

earth and having no relation to igneous rocks other than that they derived their load of metal by leaching igneous as well as sedimentary rocks. In this he follows Van Hise, who held that the important contributions of metal made to the crust of the earth from deeper-lying portions, came in the form of constituent portions of eruptive rocks and that the concentration of these materials into bodies sufficiently rich to be regarded as ores was effected by circulating meteoric waters. The illustrations here given indicate that in the Mississippi Valley at least there are types of orebodies that belong genetically with the processes of erosion and deposition. In the Lake Superior iron ores there is a suggestion of a genetic relationship with certain igneous rocks. In the copper deposits of the same region, described by A. C. Lane, there is more than a suggestion of such a relationship at the same time that the ores are correlated with certain types of sedimentary rocks. In the fluorspar veins of southern Illinois,[11] not described in this volume, there are found true veins of the Western type undoubtedly formed through the action of deep-seated heated waters. The contrast between the fluorspar veins and the typical ore deposits of the Ozark and Wisconsin regions, emphasizes the difference in genesis.

There was a prompt and strong reaction from the position taken by Van Hise, particularly by those whose interest was mainly in Western ores. The points of attack were as follows: (1) It was held that the larger number of ore deposits, having in mind especially those containing gold, silver, or copper, showed definite relations to particular masses of igneous rock; (2) that surface waters did not, as a matter of fact, penetrate to depths in the abundance necessary to the formation of ores; (3) that juvenile waters rather than meteoric must be appealed to for the formation of the deposits in question; (4) that important contributions of material were made by these waters and that the invading eruptive rock made direct contributions of metal as well as of heat and energy. These ideas, and the evidence upon which they rest, are discussed in this volume by J. F. Kemp in his description of contact deposits. To his energy and ability they owe much of the present sound basis upon which they stand. Waldemar Lindgren, especially in his description of the Clifton-Morenci district of Arizona,[12] contributed greatly to the establishment of these points. J. E. Spurr, A. C.

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[11] 'Fluorspar Deposits of Southern Illinois,' H. F. Bain, U. S. Geol. Surv., Bull. 255, p. 75, 1905.

[12] 'Copper Deposits of Clifton-Morenci District, Arizona,' U. S. Geol. Surv., Prof. Paper 43, Washington, 1905.

Spencer, F. L. Ransome, W. H. Weed, T. A. Rickard, and many others took part in the discussion, and gradually it came to be recognized that at least in the genesis of the types of ore deposits common in Western North America, magmatic waters played an important rôle. Quantitative expression of the fact has not been easy, nor is much definite information available even now as to the actual amount of water yielded by eruptive rocks. To the last S. F. Emmons maintained a quite conservative attitude toward this newer development of theory, and so keen and experienced an observer as J. Malcolm Maclaren occupies a notably different position regarding the probable direct influence of magmatic waters, from that taken, for example, by J. E. Spurr. There is a small but important minority of observers who retain doubts as to the quantitative importance of magmatic waters. In general, however, it is fair to say that differences of opinion now are mainly as to emphasis and the extent to which the ideas of J. H. L. Vogt, J. F. Kemp, Waldemar Lindgren, and others of that school are to be applied. Occasionally the difference is a matter of terms and of personal estimate as to the relative significance of the processes. Where a lean primary segregation has been formed by magmatic contact action, and this has later been enriched by surface agencies until the rock becomes an ore, it is a matter of opinion as to which should be called the ore-forming process and accordingly as to which of two classes of deposits the particular orebody may be said to belong. F. L. Ransome, in describing the Bisbee, Arizona, deposits in 1904,[13] illustrated how the same facts might be fairly interpreted in two somewhat different ways.

In the chapters in this book by S. F. Emmons, O. H. Hershey, T. A. Rickard, J. F. Kemp, F. H. Hatch, and J. D. Irving, types of deposits are discussed all of which are believed to have been formed by deep-seated heated waters. The descriptions reflect fairly the different degrees of emphasis placed by different engineers on various details of the general process. The Cobalt deposits are described by Mr. Emmons as the roots of old veins greatly enriched by repeated secondary action. The Treadwell deposits, according to Mr. Hershey, are primary gold ores owing little to secondary influences. The saddle reefs of Bendigo, described by Mr. Rickard, form a special type of deep-seated vein in which structure has led to a markedly unusual form. The contact deposits treated by Mr. Kemp exemplify excellently the influence of magmatic waters in

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[13] U. S. Geol. Surv., Prof. Paper 21, pp. 146-160.

ore formation. The conglomerates of the Rand, described by Mr. Hatch, are admittedly the most anomalous and puzzling of the great gold deposits of the world. He sets forth clearly the phenomena that connect them as to genesis with ordinary quartz veins, and it may be remarked in passing that the presence of pyrite without marcasite, in the light of Mr. Allen's investigations, to which reference has already been made, strongly confirms Mr. Hatch's conclusions. Pyrite speaks of warm alkaline waters rather than of the sea water that must be assumed to have been active in case the Rand conglomerates be held to be fossil placers. Mr. Irving, in discussing replacement deposits, ranges widely, but shows the intimate relations of this process to a wide variety of types of orebodies. In the chapters by W. H. Emmons and R. A. F. Penrose, Jr., certain broad features of ore deposits in general are discussed in the light of recent knowledge.

The whole series of chapters emphasizes not only the diversity but a certain unity of modern views. Replacement, the process discussed in especial detail by Mr. Irving, is called into requisition by practically all the writers. Few large bodies of ore are now considered to have been formed wholly through filling of preëxisting cavities. Secondary enrichment, also, is widely recognized. The explanation of this group of phenomena may be fitly characterized as the most fruitful advance made by economic geologists in the last quarter century. As early as 1855 J. D. Whitney had ascribed the origin of the rich belt of chalcocite formed under the gossan at Ducktown, Tennessee, to leaching of the latter by surface waters, and in 1880 S. F. Emmons had found a concentration of silver at the bottom of the zone of oxidation. In 1892 Mr. Penrose had, in discussing the 'Superficial Alteration of Ore Deposits,'[14] analyzed the processes of weathering of lodes, and L. Delaunay, a little later, presented a philosophic discussion of the effects of oxidation in enriching certain zones, illustrating his conclusions from his observations in Mexico. In all these cases, however, the action had been assumed to cease at the ground-water level, the enriching solutions being believed to be promptly diffused when brought into contact with the general body of underground water. A. A. Blow had, however, referred zincblende exceptionally rich in silver to secondary enrichment, and James Douglas had made a similar suggestion regarding copper sulphides at Butte (1891), and Bisbee (1900). In 1899 John M. Sully had recognized the Santa Rita cop-

[14] *Jour. Geol.*, Vol. II, p. 288.

per deposits as secondary concentrations likely to give place in depth to leaner bodies of pyrite.[15] H. V. Winchell came in the late nineties to have a clear concept of the process of secondary enrichment and to use it in his work at Butte. Complications over lawsuits then pending prevented his publication of the matter.

In 1900 at Washington occurred one of those striking instances where an important truth is announced simultaneously by different investigators. S. F. Emmons, W. H. Weed, and C. R. Van Hise each read papers, independently prepared, and each describing in detail the process of secondary enrichment of sulphide orebodies essentially as now understood. In the ten years that have since elapsed, during which the applicability of this theory has been steadily widened by field studies, important advances have been made by various investigators by experimental work in the laboratory, in determining the actual reactions which must have taken place to produce the observed results, the effects which climate and other modifying causes may have had upon the processes involved, and other matters. There still remains much to be learned in these regards, but the economic applications of the theory have already yielded most important results, especially in the development of the porphyry copper deposits. W. H. Emmons has worked out the relations of manganese to the secondary enrichment of gold deposits, and presumably other similar relations are yet to be discovered.

A review of the past should afford suggestions for the future, and it remains to inquire what, if any, light is shed on the future study of ore deposits by this résumé. First and foremost, it is evident that there are many types of deposits and that no single theory, however broad, can be expected to explain them all. If it takes all sorts of men to constitute society, it is also eminently true that many sorts of ore deposits enter into the world that forms the stage for society. Second, it is apparent that discussions as to the relative importance of different processes are not particularly profitable. The conclusion must remain largely one of personal opinion, not to say preference, until quantitative methods of geological work make notable advance. It is possible to divide all men into two classes; those that carry sharp pocket-knives, and those that do not. The classification, however, is not particularly significant, and some of the divisions regarding ore deposits that have been proposed are of but little, if any, greater value. Third, the need of more refined methods of investigation, particularly the

[15] Private report to Santa Rita M. Co., cited by L. C. Graton, U. S. Geol. Surv., Prof. Paper 68, p. 316.

development of geo-physical researches, is evident. In far too many cases the geologist is forced to be content with a hypothesis. Methods that permit testing these hypotheses by experiment are the greatest need of the present. Fourth, a larger body of accurately determined facts is required for final conclusions. There are too many places where facts of great importance have not been recorded. Drifts are abandoned, stopes cave, and notes on phenomena that do not seem at the time of great significance, are lost. At a later period, in the light of new discoveries, a careful record would prove invaluable. Fifth, the time seems to have come for much less generalization from the study of single types or districts, but when careful comparative studies of several such, promise to yield most important results. Good beginnings have been made, but the field is wide and open. Patient intelligent study of ore deposits is as likely now to prove of large scientific and economic value as at any time in the past. If this book serves to stimulate its readers to that sort of study, its authors and its editor will feel well repaid for the work that has gone into its writing.

THE CLINTON TYPE OF IRON-ORE DEPOSITS.

By C. H. Smyth, Jr.

The Clinton iron ores derive their name from the village of Clinton, Oneida county, New York, where they constitute a small, but interesting and important, part of an assemblage of sedimentary rocks to which the early geologists of the State, some seventy years ago, gave the name 'Clinton Group'. Subsequently, the name was extended to include a widespread series of rocks and associated ores similar in character to those at Clinton, and of approximately the same age. While in some cases the correlation was incorrect, the fact remains that ores fully entitled to be classed as of Clinton age exist over a considerable part of the Appalachian region. Throughout this large area, both the ores and the associated rocks vary so little in essential character that a description of their main features, as shown at the type locality, will suffice, with slight modifications, for the formation as a whole.

The rocks at Clinton are chiefly shales and impure calcareous sandstones, with a very small amount of impure limestone, and the iron ores. The lower and middle parts of the formation are chiefly shale, with thin sandy layers, the sandstone, most of which is fine grained, increasing toward the top. The ores lie, roughly, near the middle of the section, but since the formation as a whole has never been carefully studied, and neither the upper nor the lower limit definitely fixed, more precise placing of the ore is impossible at present. Obviously, in view of these facts, no exact thickness can be stated for the Clinton rocks, but it amounts to something like 200 feet, of which the ore makes up not more than four to six feet.

At most points where the ore is exposed, the rocks are sensibly horizontal, but where a given horizon is traced from point to point it is found to dip about 150 ft. per mile in a southwesterly direction. Where most of the mining has been done, on the hills just east of Clinton, the ore appears at three horizons, constituting here, as elsewhere, distinct strata, interbedded with the associated sediments as perfectly normal members of the series. The lowest ore stratum, or bed, resting upon a thick body of shale and thin sandstone beds, is about one foot thick, brick red in color, and decidedly oölitic in texture. Being of low grade, this ore is never worked, and is rarely exposed in the course of mining operations. On this account, together with its small thickness, its areal extent is not accurately known. Apparently it is a local lens, which does not continue to the west side of the valley, where, so far as I can learn, it has never been struck in any of the workings. This 'bottom tier', as it is locally called, is overlain by one to two feet of very hard, rather coarse-grained shale, on which rests the second bed of ore. This stratum averages perhaps two feet in thickness, is distinctly oölitic, like the lower bed, but of a darker red color, with a tinge of purple. There is sometimes a suggestion of metallic lustre, like that of the harder hematites, and, very rarely, tiny spots occur which are distinctly specular. This bed is the only one of present commercial importance, and all the mines of the vicinity are in it. Thus it has been traced and worked over an area of several miles, and throughout maintains a remarkably uniform character, as to both structure and composition. Above this bed lie some twenty feet of shale and thin sandstone, and then comes the third ore-bed, which is quite different from the others. This bed is much less sharply defined than the other two, passing more or less gradually into the enclosing rocks, and hence showing greater variation in thickness, with an average of perhaps two or three feet. The rocks immediately below and above are impure, calcareous sandstones instead of shale, the latter making up a minor part of the section from this horizon upward. The texture of the ore in this bed is entirely different from that of the two lower beds. The grain is much coarser, and instead of the remarkably uniform dimensions shown by the spherules of the oölite, there is much variation in size of the individual grains, and even greater variation in their shape. Close inspection shows that fragments of fossils play an important part as constituents of the ore, and with them are mingled many irregular frgments of uncertain origin. This variation in texture is paralleled by a similar variation in composition. As a rule, the ore is lean, so much so that no attempt has been made to work it in many years, in spite of its considerable thickness, but occasionally the content of iron is surprisingly high, indeed is reported to have exceeded 60% in one analysis.

On account of its thickness and intimate association with sandstones, this bed is much more often seen in natural exposures than either of the others, and is not uncommonly shown in quarries, so that while of no present importance as a source of iron in this vicinity, it is the most conspicuous of the ores, and has, apparently, the widest distribution. For the most part, the ores worked farther west in New York resemble in texture this upper ore (known locally as 'red flux') rather than the lower, oölitic, varieties, the latter seeming to be best developed in the vicinity of Clinton.

From the foregoing description, it is evident that the Clinton ores are of the bedded type, in the strictest sense, not merely presenting a superficial and deceptive resemblance to true beds, but forming an essential part of the sedimentary formation in which they occur. Indeed, in view of the unusual nature and relative thinness of the ore strata, their persistence in the Clinton rocks is striking, for, while they are by no means co-extensive with the formation, they are common in it and give to it a distinctive character. Of course, these ore beds, like other sediments, are mere lenses which pinch out laterally, but, like sediments in general, they are very thin lenses, and, moreover, when they pinch out, other ore lenses come in to take their places in the formation, though often with considerable gaps and greater or less change of horizon.

Westward from Clinton, the ores have been mined at various points, but everywhere there is a strong resemblance to the type locality, with such variations in detail as suggested above. The oölitic variety becomes less important, while an ore resembling the red flux, but more uniform in composition, takes its place. At Ontario, in Wayne county, this ore lies on shale, but is capped by a light gray limestone, quite unlike anything at Clinton. In the gorge of the Genesee river, the ore, though present, is lean and hard, while east of the Niagara river it drops out.

In Dodge county, Wisconsin, there are some thick lenses of ore capped by limestone. The ore is rather fine grained, oölitic, somewhat hydrated, and quite incoherent, but in all essentials closely resembles the oölitic ore at Clinton. It has generally been considered as Clinton in age, but in a recent letter[1] E. O. Ulrich states that it is older, probably latest Richmond. He also says that the recently mentioned[2] ore in Missouri, supposed to be Clinton, is "in the upper part of the Kinderhook series, to be more exact, in or

[1]Letter to the writer, dated December 7, 1909.

[2]Hayes, C. W. 'Iron Ores of the United States,' U. S. Geol. Surv. Bull. No. 394, 1909, 'Conservation of Mineral Resources,' p. 86.

at the base of the recently defined 'Fern Glen' formation of Stuart Weller." Both of these ores, however, though not of Clinton age, afford evidence of similar conditions at different geologic times, and from the genetic point of view, the Wisconsin ore is of interest in being capped by limestone, while the Missouri ore is noteworthy as an example of ore of Clinton type lying at great depth. The bearing of these phenomena will appear later.

Southward from the type locality, the Clinton ores appear first in Pennsylvania, where, on account of Appalachian folding, they have many miles of outcrop. Much remains to be done upon the stratigraphy of this region, and it may turn out that some ores now called Clinton are, in reality, of different age. But, be this as it may, many of the ores so closely resemble those of Clinton that there can be no doubt of their formation by identical processes, even if at somewhat different time. On the other hand, some of the ores present different aspects, and may represent different conditions of accumulation.

Farther south along the Appalachian belt, the ores occur widely, finally reaching their maximum development in the Birmingham district of Alabama. In spite of the wide separation between the two regions, the ores of the Southern States present a striking resemblance to those of New York, particularly the non-oölitic variety of the latter, and while, in the vicinity of Birmingham, the associated rocks are quite different, in northwest Georgia, to the west of the base of Lookout mountain, the exposures at the mines present a striking resemblance to those at Clinton, differing chiefly in a greater dip of the strata.

Indeed, emphatically the most remarkable feature of the Clinton ores is their practical uniformity of character over so wide an area. It was this fact that, years ago, forced me to abandon my original idea that perhaps they might result from different processes at different points,[3] and to conclude that, with few exceptions, all the Clinton ores must have the same origin.[4]

This is a rather difficult conclusion to accept, since, whatever explanation of the ore is adopted, practical uniformity of conditions over this great area is demanded. Moreover, if, as I believe, the ore is a primary precipitate, the conditions postulated are distinctly exceptional. But however difficult it may be to account for such

[3]Smyth, C. H., Jr. 'On the Clinton Iron Ores,' *Am. Jour. Sci.*, 3d Ser. 43, 1892, p. 495.

[4]'Die Hämatite von Clinton in den östlichen Vereinigten Staaten,' *Zeits. f. prakt. Geol.*, August 1894, p. 312.

conditions, the facts demand them, and analogous and equally difficult situations are by no means rare in geology.

As appears from the foregoing brief outline of the distribution and mode of occurrence of the Clinton ores, they are everywhere associated with ordinary sediments of comparatively shallow-water origin, and the most important point to be kept in mind with reference to the question of genesis is that the ores themselves are sharply defined strata, of nearly uniform character over wide areas. The latter statement holds good not only for the larger features of the ores, but also with reference to minor details, so that again, in a general way, a description of the varieties shown at the type locality holds good, with little modification, elsewhere.

As to chemical composition, the ores are lean, seldom exceeding 50% of iron and commonly containing less than 40%. The predominant impurity is generally either silica or calcium carbonate, with small amounts of magnesia and alumina. Manganese is rarely present save in small quantity, sulphur is low, but phosphorus high, often reaching 0.5% or even more, thus placing decided metallurgical limitations upon the ores. The silica and calcium carbonate vary greatly in amount, and, being the chief impurities, largely control the value of the ore, which, as the one or the other increases in amount, becomes lean, and either silicious or calcareous, as the case may be.

The physical character of the ores is everywhere practically identical with one of the two varieties shown at Clinton, or is a mixture of the two. As already stated, the typical oölitic ore is rather exceptional, the prevailing variety being the so-called fossil ore, made up of very irregular fragments of quite diverse sizes. Mixtures of these fragments with spherules like those of the oölite are not uncommon. The fragments of the fossil variety are also sometimes mixed with fossils that are well preserved, showing little effect of wear.

Everywhere, the individual particles of the ores, when closely examined, have a marked concretionary texture, this being true of all varieties, but showing most clearly in its oölitic varieties. A spherule of the oölite, or irregular fragment of the fossil ore, when lightly hammered, scales off in thin concentric shells, while thin sections under the microscope usually show the concentric structure in spite of the opacity of the earthy hematite. But this structure is better shown, while at the same time another feature is brought out, by digesting spherules and fragments in hydrochloric acid. The result of the treatment is to dissolve the iron oxide, but the grains, instead of disappearing or diminishing in size, retain their original size and shape, becoming white and translucent. Under the microscope they are seen to consist of concentric shells which may be torn apart by a needle. The material of these shells is either dark with crossed nicols, or shows the cross of aggregate polarization. It is readily soluble in fixed alkalies, and, though it has not been analyzed, is probably amorphous silica.

In the case of oölitic spherules, the dissolving of this silica coating leaves, as a rule, a small core of thoroughly rounded quartz. Thin sections of the ore show these cores to be made up of quartz derived from crystalline rocks, with all the characteristic inclusions. Thus, the typical spherule of the oölitic ore consists of a core of detrital quartz surrounded by concentric shells consisting of an intimate association of hematite and, probably, amorphous silica.

In the case of the fossil ore, many of the grains are strictly analogous to these spherules, differing merely in the fact that instead of a grain of quartz, a fragment of some shell, crinoid stem, or similar substance, serves as the core, around which the shells of iron oxide and silica have gathered, at the same time filling in all cavities of the fragment. Other grains, however, are more complex, as, before being coated, the calcium carbonate of the fragment has been more or less completely replaced by iron oxide and silica. When such a grain is digested in acid, the concentric shells of silica may be removed with a needle, and inside will be found the form of the original fossil fragment preserved in the same amorphous silica. As the fossils concerned usually are mere fragments, whose inner structures are very minute, it is by no means easy to distinguish between cases of actual replacement of the fossil and mere filling of all its cavities, but with this one qualification, the phenomena described have been observed in a large number of specimens, representing the most widely separated occurrences of the Clinton, as well as the Wisconsin ore referred to above. In no case examined has either the concentric texture or the association of iron oxide with amorphous silica been lacking. Similar phenomena have been noted by others in connection with several oölitic ores, but not, so far as I am aware, in anything similar to the fossil ores.

Here again, in the minute features of the ores, just as in their broad geological relations, the striking fact is their essential uniformity, indicating in a most positive manner that, whatever difficulties are involved, the only possible conclusion is that they were formed by one and the same process of concentration, resulting from practical unity of conditions over a large area. As to the nature of this process, there is considerable difference of opinion, though, except for details, the matter resolves itself into a question between two methods of concentration; primary precipitation and replacement. Derivation from a ferruginous limestone, sometimes considered as a third method of concentration, is here treated merely as a special variety of primary precipitation.

The first hypothesis holds that the iron was brought, in solution, into shallow, and perhaps enclosed, basins, and was there precipitated by oxidation, reaction with the calcium carbonate of shells, the action of bacteria, algae, or other organisms, and perhaps other agencies to which there is no clue. In other words, according to this explanation, the ores are analogous in origin to the lake ores which are forming in many places at the present time. The two essential points of this hypothesis are: (1) the introduction of the iron into the basins of sedimentation in solution, and (2) its direct precipitation there; the iron ores thus being integral members of the stratified series in which they occur, and each bed of ore younger than the stratum beneath it and older than that above it. In other words, the ores are primary.

A great many questions present themselves as to the source of the iron, the nature of the solutions, the reactions leading to precipitation, the chemical nature of the iron compounds precipitated, and possible subsequent alteration, but from the purely geological point of view these are of minor importance, and to be considered only after the main thesis, that the ores are primary, has been established.

This view of primary origin of the ore was generally held by our earlier geologists,[5] but later the replacement hypothesis was strongly urged[6] and somewhat generally accepted.

According to this latter view, there was no very marked concen-

[5]Hall, James, 'Geology of New York,' Pt. IV, 1843, p. 60. Rogers, H. D., *Proc.* Boston Soc. Nat. Hist., VI, pp. 340-341, 1858, and Geol. Penn. II, p. 729. Newberry, J. S., Geol. Surv. of Ohio, III, pp. 5-7, 1879. Chamberlin, T. C., Geol. of Wisconsin, I, p. 179, 1883.

[6]Shaler, N. S., Ky. Geol. Surv., Pt. III, Vol. III, 2nd Ser., p. 163, 1877. Foerste, A. F., 'On the Clinton Oölitic Iron Ores,' *Am. Jour. Sci.*, 3d Ser., 41, 1891, pp. 28-29. Kimball, J. P., 'Genesis of Iron Ores by Isomorphous and Pseudomorphous Replacement of Limestone,' *Am. Geol.*, VIII, 1891, p. 352. Rutledge, J. J., 'The Clinton Iron Ore Deposits in Stone Valley, Huntingdon County, Pennsylvania, Am. Inst. Min. Eng., *Bi-Monthly Bull.* No. 24, 1908, pp. 1057-1087.

tration of iron in any of the Clinton rocks, as originally deposited, but merely the usual iron content of limestones, shales, and sandstones. The concentration of iron into ores is considered as entirely secondary, the work of ground waters, which are assumed to have passed down through sandstones and shales, dissolving out iron as bicarbonate, sulphate, or organic salts, this iron being precipitated by, and replacing, limestones with which the solutions came in contact.

Thus, the two views are sharply contrasted, the one regarding the ores as formed by precipitation in surface waters, and primary; the other, as formed by underground waters, and secondary. The conditions involved are totally different, and while it may be true, as F. W. Clarke says,[7] that, from the chemical point of view there is no great difference, from the geological point of view the difference is fundamental.

The conclusion that the ores resulted from primary deposition was doubtless based upon their occurrence over wide areas as clearly defined members of a sedimentary series, constituting distinct strata, often of quite uniform thickness and considerable horizontal extent. This mode of occurrence is in marked contrast with that of replacement deposits in general, as they are usually quite irregular in form, localized, and 'pockety'. After the lapse of half a century, this distribution and form of the ores still constitute the most striking evidence of their origin and emphatically put the burden of proof upon those who support any explanation other than that of primary deposition.

The idea of replacement originated partly in the difficulty of explaining the concentration of so much iron in marine waters, partly in the relation between the iron oxide and fossils, and, perhaps most of all, in the frequently observed decrease in iron and increase of calcium carbonate as the ores were followed below the level of active circulation of meteoric waters. These are all matters of importance in connection with the question of genesis, and the two last, in particular, demand consideration. That they may be wholly reconciled with primary deposition is confidently believed.

The concentration of iron in marine waters demanded by primary deposition is admittedly difficult to account for, but this does not justify the abandonment of an explanation which is demanded by a large number of facts. Why the particular adjustment needed to furnish an unusual amount of dissolved iron compounds

[7]'Data of Geo-Chemistry,' Bull. U. S. Geol. Surv. No. 330, 1908, p. 453.

should characterize the Clinton, rather than other Paleozoic periods, does not appear, but there are similar difficulties in connection with many other geologic phenomena. Indeed, it would be at least as difficult to explain why, in the Clinton, there should be a secondary concentration of originally diffused iron, by replacement, into widely extended stratiform deposits, and so few, if any, similar cases in the other Paleozoic formations.

The fact that the ore is often largely made up of fossils, for the most part quite fragmentary, which is also pointed to as evidence of secondary origin, is capable of, and indeed, for many cases demands, a different explanation. In the first place, it often happens that the fossil fragments are merely coated with iron oxide, just as, in other cases, pebbles and grains of quartz are coated. But further than this, there is strong evidence that, when the calcium carbonate of shells has been actually removed and its place taken by iron oxide, the process occurred during the accumulation of shells on the sea bottom. Apparently, the iron was held in solution in the sea water, to be precipitated by, and replace, the calcium carbonate of the shells. Thus the shells were replaced as they accumulated, and a bed of fossil ore was formed, with its present iron content, before the deposition of the overlying bed of mud or sand. In other words, the water being strongly charged with iron, some of this was deposited by oxidation or action of organisms, to build up the oölitic ores, while another portion was simultaneously deposited by the process described to form the 'fossil ore'. Naturally, sometimes one, sometimes the other process would predominate, giving the one or the other variety of ore, while in other cases a mingling of varieties would occur; and all these conditions we find illustrated in the existing ores. An interesting confirmation of this view is afforded by the work of F. B. Loomis,[8] who, in discussing the influence of impure, and particularly ferruginous, waters upon the organisms living in them, calls attention to the fact that the fossils in the Clinton ores are smaller than the same species in the associated rocks. This he explains as due to the large quantities of iron salts in the waters at the time that the ore strata were accumulating.

Of the various phenomena leading to the conclusion that the replacement of fossil fragments was of the primary nature indicated, rather than the work of underground waters, there is one particu-

[8]Loomis, F. B. 'The Dwarf Fauna of the Pyrite Layer at the Horizon of the Tully Limestone in Western New York,' N. Y. State Museum Bull. 69, 1903, p. 895.

larly striking group which may, perhaps, be best presented by describing certain features of the ore at a special locality. Near the village of Ontario, Wayne county, New York, the ore is of the fossil type, and about two feet thick. The cover is thin, sometimes only glacial material, but when rock, the latter is a pure, light gray limestone. The rocks are sensibly horizontal. Assuming the replacement hypothesis to be correct, the ore represents the lower part of the limestone from which the calcium carbonate has been dissolved, and its place taken by iron oxide. The iron has been leached out of overlying rocks by ground waters, carried down till it came in contact with the bottom beds of limestone and then precipitated. But a serious difficulty arises. If limestone is capable of precipitating the iron from its solution, how did the latter carry its burden of iron down through the overlying limestone with no trace of any reaction between the two, and then suddenly attack the bottom layers? Furthermore, replacement by downward-moving waters (if, by any chance, it could affect the bottom layers of limestone and not those above, through which it had to pass before reaching the bottom layers) would be expected to produce an ore deposit of irregular thickness and varying composition, best developed adjacent to joints, with an irregular contact, as well as a gradual transition, between it and the limestone. But this is far from the case. The ore is of uniform thickness and composition, and has an even and sharply defined upper contact with the limestone. This contact is particularly instructive. As already stated, the transition from limestone to ore is abrupt, the only blending of the two being mechanical rather than chemical. This appears in the fact that, in the bottom layer of limestone there are many fragments identical in character with those of which the underlying ore consists. These fragments are scattered through this layer of limestone, are completely surrounded by pure limestone, into which they show no gradation, and are themselves as rich in iron as are the fragments of the ore below. That these ferruginous fragments in the limestone have been formed there by replacement is difficult to believe. On the contrary, it seems perfectly clear that they had their present iron content when they were first incorporated into the limestone, being simply fragments of the still incoherent bed of ore upon which the limestone was deposited.

If phenomena of this kind were confined to the one locality, they would, perhaps, hardly merit so much consideration, but as a matter of fact, while varying in detail, they may be seen practically wherever the ores occur. Ore beds are repeatedly covered by calcareous shale and sandstone, if not actual limestone, through which percolating waters would have to carry their burden of iron to be precipitated by the calcium carbonate supposed, by the replacement hypothesis, to have occupied the place of the existing ores. And whenever lean ores are examined they show highly ferruginous spherules or fossil fragments entirely surrounded by pure calcite, and evidently in practically the condition in which they reached their present positions.

In the lean fossil ores, it often happens that highly ferruginous, slightly ferruginous, and wholly calcareous fragments are mingled together in the most chaotic fashion, with no gradual change in amount of iron either across or along the bedding, such as would naturally result from an introduction of iron into a compact mass. Each fragment seems to have been a law unto itself, drifting about in the chalybeate waters and becoming mingled with other fragments, which had received more or less iron, as the case might be, the whole finally coming to permanent rest and forming the heterogeneous mass now found. Low-grade ores of this type occur in practically all Clinton ore regions. By weathering they may become fairly rich through solution and removal of calcium carbonate. Then, when worked to any depth, the ores present their original character, becoming low grade and calcareous, and suggest, in consequence, the idea of genesis by replacement of limestone, or even the derivation of the ores from the mere weathering of ferruginous limestones, as maintained by I. C. Russell,[9] the inaccuracy of whose data has recently been shown by E. C. Eckel.[10] In the other, and much more important, cases, where fossil ores are richer and more uniform in character, it is probable that, after the accumulation of the fragments into an incoherent bed, further deposition of iron from the waters occurred before the overlying bed of mud, sand, or calcareous ooze was formed. This method of formation of the fossil ore is well exemplified by the shell deposits now accumulating on the bottom of Lake Fureso, Denmark, where, as described by C. Wesenberg-Lund,[11] shells occur in all stages, from fresh and un-

[9]Russell, I. C. 'Subaërial Decay of Rocks and Origin of the Red Color of Certain Formations,' Bull. U. S. Geol. Surv. No. 52, 1889, pp. 22-23.

[10]Eckel, E. C. 'Iron Ores, Fuel, and Fluxes of the Birmingham District, Alabama,' Bull. No. 400, U. S. Geol. Surv., 1910, pp. 29-30.

[11]Wesenberg-Lund, C. Medd. Dansk. Geol. For. No. 7, 1901, pp. 79-87 and 159, Plates I and II.

changed, through those that are coated with limonite to those that are completely replaced. He states that even living shells have the iron coating. The analogy between this material and the fossil ore is striking, and parallel to that existing between the so-called flax-seed lake ores and the oölitic Clinton ores.

The case with the oölitic ores is slightly different. These ores, as a rule, are quite homogeneous, at least in so far as the individual spherules are concerned. The amount and character of interstitial material may vary considerably, but, in any given bed, the spherules are, with the minor exceptions noted below, remarkably uniform in character, while, unlike the fossil fragments, they never become calcareous. When a purely oölitic ore is lean, it is on account of an increase of non-ferruginous interstitial material, or larger cores of quartz in the spherules, rather than because the spherules themselves are calcareous. This is so distinctly the case that it is probable that the idea of replacement would never have been advanced for the Clinton ores, had the oölitic variety only been concerned.

But perhaps the chief argument in favor of replacement lies in the fact, very generally observed where the ore beds have a marked dip, that they become calcareous and correspondingly leaner, when mined below the permanent ground-water level. This fact has been made the basis for the unwarranted assumption that the change would progress steadily with depth, so that the iron ore would soon give place to limestone. In a recent paper E. C. Eckel[12] calls attention to "two errors, one of observation and one of interpretation", which have done much to perpetuate this view. It is upon this point that the practical importance of the genetic question turns, since, as is manifest, the persistence of the ores is contingent upon their being primary, while, on the other hand, if of replacement origin, they must necessarily be of limited depth.

In my early discussions of the ores,[13] the position was taken that the ores were primary, and would be found to continue in depth, with the original iron content, any enrichment of the more superficial portions being merely relative, and due to the solution and removal of calcium carbonate by meteoric waters. As bearing directly upon this matter, attention was called to the deep borings

[12] 'Iron Ores, Fuels, and Fluxes of the Birmingham District, Alabama,' Bull. No. 400, U. S. Geol. Surv., 1910, pp. 28-29.

[13] Smyth, C. H. Jr. 'On the Clinton Iron Ores,' *Amer. Jour. Sci.*, 3rd Ser., XLIII, 1892, pp. 487-496. 'Die Hämatite von Clinton in den östlichen Vereinigten Staaten,' *Zeits. f. prakt. Geol.*, II, 1894, pp. 304-313.

at Syracuse, New York, reported by C. S. Prosser,[14] in which the Clinton ore was struck at depths of 976 and 995 feet, respectively. Subsequent events, and particularly the extensive mining of Clinton ore in the South, have amply justified the above conclusion, and, at the same time, have removed the chief support of the replacement hypothesis. It is needless to give detailed data in regard to the developments referred to, the following examples sufficing to make the matter clear. As the result of an extended series of borings made by the New York State Geological Survey, D. H. Newland and C. A. Hartnagel[15] say, "recent exploration with diamond-drill has shown that there is no notable change in character on the dip for a distance of five or six miles from the outcrop." The nature of the overlying rocks, together with the topography of the region, is sufficient evidence that these ores have been but little influenced by ground waters, and must be in nearly their original condition. But even stronger evidence is afforded by the extensive mining operation in the South. E. F. Burchard[16] says: "Experience in mining the ore in every slope in Alabama that has passed beyond ground-water level shows that the ore does not give place to a thicker bed of slightly ferruginous limestone, but rather to an almost uniformly calcareous ore, whose richness apparently depends on the quantity of iron originally included in the sediments." He further states (p. 1043): "A number of borings in Alabama have struck the ore at points 0.5 to 1 mile back from the outcrop, and at depths of from 400 to 800 feet below the surface. The ore in these borings was hard ore of the usual quality, and not merely ferruginous limestone." According to the same authority (p. 1024) ore was being mined, in 1908, at a vertical depth of 650 feet. H. S. Chamberlain[17] states that the mines of the Roane Iron Co., in Tennessee, are working Clinton ore "1200 ft. down on the dip, which corresponds to 800 ft. vertical depth below the outcrop, and the ore is fully as rich and valuable at the bottom as it was at the surface when the mine was first opened."

Such phenomena are what would be looked for on the assump-

[14] Prosser, C. S. 'The Thickness of the Devonian and Silurian Rocks of Central New York,' Bull. Geol. Soc. Am., IV, 1893, pp. 99-102.

[15] Newland, D. H., and Hartnagel, C. A. N. Y. State Museum Bull. No. 123, 1908, 'Iron Ores of the Clinton Formation in New York State,' p. 51.

[16] Burchard, E. F. 'The Clinton Iron Ore Deposits in Alabama,' Amer. Inst. Min Eng. *Bi-Monthly Bull.*, No. 24, 1908, p. 1042.

[17] Chamberlain, H. S. Discussion of paper by J. J. Rutledge, 'Clinton Iron Ore Deposit of Stone Valley, Huntingdon County, Pennsylvania,' Amer. Inst. Min. Eng. *Bi-Monthly Bull.*, No. 25, 1909, p. 108.

tion that the ore is primary, while, on the other hand, they are difficult to reconcile with the replacement hypothesis, and diametrically opposed to deductions drawn from it. If the evidence for primary precipitation was strong twenty years ago, the results of mining during the interval have certainly made it much stronger, approximating, in my opinion, as near to a demonstration as is likely to happen in the case of an ore deposit. But while the case for primary deposition seems well established, to remove all difficulties and explain all details is a very different matter, and many minor problems present themselves for which there can hardly be any hope of solution.

As regards the precise nature of the chemical reactions involved in the primary precipitation of the ores, little need be said. There is much reason for skepticism with reference to the equations commonly employed to express the reactions by which iron is precipitated from natural waters, and while they may have a schematic value, and indicate the initial and final stages of processes, they give a deceptive appearance of simplicity, when the actual pheomena are doubtless extremely complex. The work of J. H. Van Bemmelen along this line, while marking progress, shows how much remains to be learned. In a paper[18] on bog ores, after reviewing the question of the chemical reactions involved in their genesis, he says: "this shows how exceedingly scanty is our knowledge of the formation of iron compounds in nature." That the iron was dissolved from rocks and soils as ferrous salts, brought into the sea and there precipitated by oxidation, action of calcium carbonate, organisms, and other agencies, may be regarded as established, but beyond this, lies a region of speculation. When the chemistry of modern lake and bog ores is worked out in detail, geologists will be in a position to explain the deposits of older date, but till then, it seems hardly worth while to attempt to give precise reactions.

As to the source of iron, it is to be sought in the ferro-magnesian minerals and iron sulphides and oxides of the crystalline rocks forming land areas during Clinton time. Ulrich, in the letter elsewhere mentioned, makes the interesting suggestion that the immediate source of the iron was the lower Medina, which, of course, derived it ultimately from the crystalline rocks. Obviously, both sources may have supplied iron simultaneously.

[18] Van Bemmelen, J. H. 'Ueber das Vorkommen, die Zusammensetzung, und die Bildung von Eisenanhäufungen in und unter Mooren,' *Zeits. f. Anorg. Chemie,* XXII, 1909, pp. 313-379.

Assuming a rather complete analogy with modern lake ores, it is probable that the iron was deposited, for the most part, as limonite, with, perhaps, subsidiary carbonate. The dehydration of the limonite may have followed soon after precipitation, since W. Spring[19] has shown that freshly precipitated ferric hydroxide undergoes spontaneous dehydration while still in contact with water, particularly if the latter is saline. On the other hand, dehydration may have been a slower process, aided, perhaps, by pressure of overlying rocks, and slight temperature increase.

An interesting modification of the hypothesis of primary deposition as outlined above, has recently been advocated by S. W. McCallie,[20] his view being that the iron was originally deposited not as limonite, but as glauconite. This idea was suggested to me as a possibility, several years ago, in part by certain phenomena in the field, and in part by printed descriptions of other ores, especially those of R. A. F. Penrose, Jr.,[21] on the Arkansas and Texas ores, and J. E. Spurr[22] on the Mesabi ores. But the work of C. K. Leith[23] on the Mesabi ores, and even more, perhaps, L. Van Werweke's paper[24] on the Minette ores of Lorraine, showed that this explanation could probably be applied only with important modifications, if at all. The field phenomena were briefly referred to in my earlier papers, and consist, chiefly, of the not infrequent association of green and gray oölites with the ordinary red oölitic ores. That these green oölites might have a direct bearing upon the question of ore genesis was evident, and an effort has been made to gather all data possible bearing upon this phase of the subject, but with rather unsatisfactory results. However, enough material has been accumulated to serve as a basis for the necessary microscopic and chemical work, and it is hoped that this may be finished in the near future. At present nothing can be attempted beyond a brief consideration of

[19]Spring, W. 'Ueber die eisenhaltigen Farbstoffe sedimentärer Erdboden und über wahrscheinlichen Ursprung der rothen Felsen,' *Neues Jahrb. f. Mineral, Etc.*, I, 1, 1899, pp. 47-62.

[20]McCallie, S. W. 'Fossil Iron Ores of Georgia,' Geol. Surv. of Georgia, Bull, No. 17, 1908, pp. 185-194.

[21]Penrose, R. A. F., Jr. 'The Tertiary Iron Ores of Arkansas and Texas,' Bull. Geol. Soc. Amer., III, 1892, p. 44.

[22]Spurr, J. E. 'The Iron Ores of the Mesabi Range,' *Amer. Geol.*, XIII, 1894, p. 335, and 'The Iron-Bearing Rocks of the Mesabi Range in Minnesota,' Bull. Geol. Nat. Hist. Surv. of Minnesota No. 10, 1894.

[23]Leith, C. K. 'The Mesabi Iron-Bearing District of Minnesota,' Mon. XLIII, U. S. Geol. Surv., 1903; and an earlier preliminary note in *Science*.

[24]Van Werweke, L. 'Zusammensetzung u. Entstehung Lothringisch-luxemburgischen oölitischen Eisenerze (Minetten),' Oberrhein. Geol. Verein, Separatabdruck, April 1901.

McCallie's suggestion and the facts that bear upon it. His argument is based upon the presence of a green mineral in thin sections of ore, and, particularly, upon ferrous iron shown by some analyses, which he considers as indicative of the presence of glauconite. From this he concludes that the ore was originally deposited as glauconite under conditions such as those that lead to the deposition of this mineral on modern sea bottoms. This explanation has the great merit of connecting the ores genetically with a marine deposit of a kind forming abundantly at the present time, but it is open to several serious objections.

In the first place, glauconite is a ferric, not a ferrous, silicate, and while it is true that greensands often contain ferrous iron, it is hard to see how the latter could remain unchanged during such a radical alteration as that of glauconite into hematite. The evidence afforded by the green mineral is interesting as far as it goes, but inadequate, particularly as no data are given to prove that the mineral is, in reality, glauconite. The minute texture of the green mineral, as described by McCallie, is not apparent, but, in the many sections of green oölite from Clinton, New York, that I have examined, there has always been a highly developed concentric texture, which is something that Murray and Renard[25] state specifically to be entirely absent in glauconite, while Leith[26] says the same of greenalite. This would seem to indicate that if any iron silicate has played a part in the ore formation, it can not be glauconite or greenalite, but rather chamosite, thuringite, or related ferrous silicates, which have concentric structure, and in other physical properties resemble the green oölite of Clinton. At first glance, this might appear to be a minor detail, but in reality it is of great importance, since the derivation of the ores from these minerals, if established, would lack the most important feature of the glauconite hypothesis, as it would not connect the ores with any type of deposits forming on existing sea bottoms. For, so far as I can learn, no case is known of the present-day formation of any of these ferrous silicates in the sea, and, while it is true that some authorities regard them as analogous in origin to modern glauconite, there is wide divergence of view with reference to their mode of formation. For example, while R. Beck[27]

[25]Murray, J., and Renard, A. F. 'Voyages of H. M. S. *Challenger*, Report on Deep Sea Deposits,' 1891, p. 381.

[26]Leith, C. K. 'The Mesabi Iron-Bearing District of Minnesota,' Mon. XLIII, U. S. Geol. Surv., 1903, p. 248.

[27]Beck, R. 'The Nature of Ore Deposits,' pp. 84-85.

seems to imply that chamosite and thuringite are primary precipitates, E. R. Zalinski[28] regards them as resulting from the alteration of some pre-existent sediments of unknown character. Again, while L. Van Werweke[29] considers part of the Minette ores of Lorraine to be derived from ferrous silicates which were original precipitates, R. Lepsius[30] and F. Gaub[31] take precisely the opposite view with reference to other oölites, and regard the silicate as resulting from the alteration of primary limonite. This is sufficient to show how far the presence of ferrous iron, or even of ferrous silicate, in an iron ore is from establishing its origin.

But the most serious objection to the glauconite hypothesis lies in the fact that in all instances where there seems to be good ground for regarding iron oxide ores as derived from primary silicates, whether glauconite or not, the silicates are present in such quantity as to make the connection evident, while in the Clinton ore such is distinctly not the case. McCallie states[32] that a boring in Alabama showed increase of the silicate with depth, but the evidence is totally inadequate, and is also at variance with the general experience. As stated elsewhere, the ore retains its normal character at great depths, and if this fact is difficult to reconcile with the replacement hypothesis, it has similar bearing upon derivation from silicate. While ferrous silicates might readily be oxidized to limonite at and near the surface, such a change, with anything like the completeness demanded by the actual character of the ore, is hardly possible in nearly horizontal rocks at depths approaching a thousand feet.

If the Clinton ores were found grading into glauconite, as the Mesabi ores grade into greenalite, and certain European ores grade into oölitic chlorites, there would be excellent ground for regarding the ores as derived from glauconite, and a most satisfactory explanation of their origin would be afforded. But, in spite of extensive and deep mining, this is emphatically not the case, and for this reason alone, the glauconite hypothesis appears to be untenable. Further, if the ores graded into chlorites, like chamosite, it is evident, from what has been said above, that a problem would exist

[28]Zalinski, E. R. 'Unterschungen über Thuringit und Chamosit aus Thuringen und Umgebung,' *Neues Jahrbuch f. Mineral, Etc.*, B. B. 19, pp. 81-84.

[29]*Op. cit.*

[30]Lepsius, R. Geol. von Deutschland, 2 Lief. I, 1903, p. 219.

[31]Gaub, F. 'Die Jurassichen Oflithe der Schwabischen Alb.,' *Neues Jahrbuch f. Mineral, Etc.*, 1908, II, p. 94.

[32]*Op. cit.*, pp. 190-191.

as to which was the original form, the ore or the chlorite. I have long felt that the possible derivation of the ore from chamosite was suggested by analogy with other deposits, but, as indicated above, have not been able to overcome the difficulties in the way of this view. McCallie's report is an important contribution to this side of the problem and should serve to stimulate investigation.

Before dismissing this phase of the subject, attention should be called to the fact that, as yet, so far as I am aware, no instance has been found showing a green variety of the fossil ore analogous to the green oölite, that is, one in which all the fragments are green, indicating ferrous silicate. Such an occurrence would be of much interest, and might be of considerable assistance in working out the history of the green silicates.

To the foregoing statement as to the genesis of the Clinton iron ores, perhaps a few supplementary words should be added.

While the ores are looked upon as typically and essentially primary, there is, of course, no reason why, in some cases, there may not have been a certain amount of direct secondary enrichment by ground waters. But this is confidently believed to be a minor and exceptional process, of no real importance so far as the typical ores are concerned. However, since iron ores are frequently formed by replacement, and since Clinton rocks are frequently ferruginous, there is no reason why there should not be replacement ores in the Clinton. But if such ores occur, they must lack the essential characters of the Clinton ores as above described, and their different origin must be reflected in their distribution, form, and composition. Although possessing a fairly wide acquaintance with the Clinton ores, I have never seen any which I would regard as belonging to this, for the Clinton, exceptional type.

As to the economic importance of the Clinton ores, but little need be said. That they are the chief basis of the extensive iron industry of the Birmingham and Chattanooga districts is well known, while they have been worked for a century in various parts of the great area over which they extend. That they will be of at least equal importance in the future can hardly be doubted, if, as maintained here, their origin is such as to warrant the expectation of their continuance with depth. Naturally, for ores occurring in beds of fairly uniform thickness, much more reliable estimates of total quantities available can be made than is the case with deposits of more variable form. But it is only by assuming a certain degree of uniformity of composition, in spite of increasing depth, that such estimates can be made. Upon this assumption, Newland and Hartnagel,[33] with conservative limitations of mining depth, place the available Clinton ore in New York at 600,000,000 tons. For the Birmingham district Burchard[34] estimates the total amount of ore as 796,896,800, of which probably 500,000,000 tons is at present available. For the whole of Alabama, Eckel's[35] estimate, including some thin and low-grade ores, is 1,000,000,000 tons. Hayes,[36] however, gives the total available Clinton ores at only 508,540,000 tons, while the not available is 1,620,500,000 tons, showing a difference of opinion as to what constitutes availability. Leith[37] quotes Törnebohm's estimate of 60,000,000 tons of iron ores now available in the southern Appalachian, most of it being Clinton, and says, in comment, "it is altogether likely that the tonnage of these ores is many fold the figures given", a statement amply justified by the foregoing estimates. Even if a considerable margin of error be allowed for these figures, they suffice to show that the Clinton hematites are of such magnitude as to occupy a very respectable place among the ore deposits of the world.

Similar ores are not common in the United States, being chiefly represented by the two occurrences above mentioned, in Wisconsin and Missouri, which have hitherto been regarded, doubtless incorrectly, as also Clinton. That their origin is closely analogous to that of the Clinton ores hardly admits of doubt. In Europe, the very important Minette ores of Luxembourg and Lorraine resemble the Clinton ores in many respects, and probably are of similar origin. In this case, however, it seems likely, from L. Van Werweke's[38] work, that a primary ferrous silicate may have been an important factor. However, there is wide diversity of opinion as to the genesis of these ores, and, while published descriptions indicate an analogy with the Clinton ores so close as to point to the same methods of genesis, no definite conclusion can be drawn at present. Besides the Minette, there are several other Mesozoic ores of similar char-

[33]Newland, D. H., and Hartnagel, C. A. 'Iron Ores of the Clinton Formation in New York State,' New York State Museum Bulletin, No. 123, 1908, p. 44.

[34]Burchard, E. F., and Butts, C. 'Iron Ores, Fuels, and Fluxes of the Birmingham District, Alabama,' U. S. Geol. Surv. Bull. No. 400, p. 133, 1910.

[35]Eckel, E. C. 'Review of Conditions in American Iron Industry,' *Eng. & Min. Jour.*, XXX, pp. 518, 527, 1906.

[36]Hayes, C. W. 'The Iron Ores of the United States,' Papers on the Conservation of Mineral Resources, U. S. Geol. Surv. Bull. No. 394, p. 90.

[37]Leith, C. K. 'Iron Ore Reserves,' *Econ. Geol.*, I, p. 365, 1906.

[38]*Op. cit.*

acter, in regard to whose origin there is much diversity of opinion. In several cases, chamosite and thuringite play an important part, and give added complexity to the genetic problem. Beck[39] classes these ores as bedded deposits, and thus accentuates the relationship with the Clinton ores, but it is clear that much work must be done before existing uncertainties can be eliminated.

In England, several oölitic ores have been largely worked, and the prevailing opinion seems to favor their origin by replacement of limestones, as shown by Harker's[40] recent brief review of the subject. Thomas and MacAlister[41] regard some of these ores, at least, as primary precipitates, analogous to the Clinton oölitic ores. Others, the important Cleveland ores, for example, they consider "contemporaneous replacements," assuming the iron to have coated and replaced calcium carbonate on the sea bottom.[42] This is the process that is advocated above for the fossil variety of Clinton ores, and is simply a special type of precipitation, in which the calcium carbonate, doubtless, is sometimes chemically active and sometimes passive, the calcareous fragments merely affording, in the latter case, centres of accumulation. Judging from published descriptions, many of the English ores resemble the Clinton ores so closely in essential characters, as to strongly suggest similarity of origin, and it would seem that the results of recent mining in this country might advantageously be applied to the interpretation of the English deposits. The general impression given by a survey of the English literature of iron ores is that those resembling the Clinton ores are usually regarded as replacements of limestone, unless very positive evidence to the contrary is forthcoming. Possibly this impression is not justified, but if it is, the tendency is certainly to be deprecated. Each case should be judged upon its merits, and when this is done there can be little doubt that many ores will prove to be primary sediments of the Clinton type.

[39]Beck, R. 'The Nature of Ore Deposits,' 1905, pp. 93-98.

[40]Harker, A. 'Petrology for Students,' 1908, pp. 273-275.

[41]Thomas, H. H., and MacAlister, D. A. 'Geology of Ore Deposits,' 1909, pp. 307 and 308.

[42]*Op. cit.*, p. 245.

LAKE SUPERIOR TYPE OF IRON-ORE DEPOSITS.

By C. K. Leith.

*The Lake Superior region contains representatives of nearly all known types of iron-ore deposits, but 99% of the Lake Superior ore comes from sedimentary banded iron formations of pre-Cambrian age, which may be regarded as the Lake Superior type.

GENERAL DESCRIPTION OF ORES OF THE LAKE SUPERIOR PRE-CAMBRIAN SEDIMENTARY IRON FORMATIONS.

The ores occur in three different series, the Keewatin, the middle Huronian, and the upper Huronian. The ores of the upper Huronian group are commercially by far the most important, nearly three-fourths of the ore coming from this horizon. The table on the next page shows the percentage of ore which has been mined from these series by districts from the opening of mining in the district to the close of 1909.

Notwithstanding the fact that the iron formations are contained in different groups separated by great unconformities, they are remarkably similar in their lithology, making it possible to discuss the iron-bearing formations essentially as a unit. The repetition of like iron formations in three groups separated by great unconformities in the Lake Superior region is a remarkable fact. The Lake Superior iron-bearing formations are unique with reference to most of the known sediments of the globe. The early geological conclusions relating to the structure of the Lake Superior iron-bearing formations were based on the assumption that formations so peculiar were developed at one and the same time, leading of course to much confusion in the interpretation of the stratigraphy

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of the region. An attempt is made under the following headings to summarize the salient features of the ores of the region as a whole.

State	District	Geological Horizons		
		Keewatin	Middle Huronian	Upper Huronian
Per Cent		Per Cent	Per Cent	Per Cent
Minnesota 50.06	Mesabi			43.57
	Vermilion	6.49		
Michigan 46.64	Gogebic			11.48
	Marquette		19.91	0.54
	Menominee, including Crystal Falls, Iron River, etc.		0.24	14.47
Wisconsin 3.30	Penokee			2.07
	Menominee (Florence)			1.17
	Baraboo		0.06	
Totals		6.49	20.21	73.30

KINDS OF ROCKS IN THE IRON FORMATIONS.

In the simplest terms, the iron formations consist essentially of interbanded layers in widely varying proportions of iron oxide, silica, and combinations of the two, variously called jasper, or jaspilite where anhydrous and crystalline, ferruginous chert,[1] taconite or ferruginous slate where softer and more or less hydrous. These rocks become ore by local enrichment, largely by the leaching out of silica and to a less extent by the introduction of iron oxide. There are accordingly complete gradations between them and the iron ores. Many of the intermediate phases are mined as lean sili-

[1]Chert, as defined in the text-books, is an amorphous and hydrous variety of quartz, but in the field the term has been very generally applied to silicious bands such as those found in limestone, with little regard to their microscopic or chemical characteristics. Some of the so-called cherts and limestones are very fine-grained or amorphous. The cherts of the iron formation are similar in every respect to those of the limestones. They show the same irregularity of texture, interlocking of quartz grains, and often very fine grains. However, it cannot be said that any of the so-called chert in the Lake Superior region has been found to be truly amorphous and hydrous.

cious ores. In the following descriptions, therefore, the ores are not in all cases sharply differentiated from the iron formations. Local phases of the iron formations are amphibolitic and magnetitic cherts and slates, cherty iron carbonates, ferrous silicate or greenalite rocks, pyritic quartz rocks, and many ferruginous rocks derived from the foregoing varieties. All of these phases are found in each district, but in considerably varying proportions. One of the most significant variations with reference to the origin of the ore is in the relative abundance of greenalite rocks and of siderite.

COMPOSITION OF IRON FORMATION.

The average composition of all the original greenalite and carbonate phases of the iron formations, from all available analyses, is 24.8% iron. The average composition of the ferruginous cherts and jaspers, from which there has been but little leaching of silica, from all available analyses, is 26.33%. The amphibole magnetite phases of the formation show approximately the same percentage. The average composition of the entire formation, from all available analyses, taking different phases in proportion to abundance, is 38% for the Lake Superior region. A comparison of this with the figures of 24.8% for the original phase of the formation, and 26.33% for the ferruginous cherts and jaspers from which silica has not been removed, will show what has been accomplished in the secondary concentration of the ores.

RATIO OF ORES TO IRON FORMATIONS.

It may again be noted that the iron ores, while important commercially, form but a small percentage of the rocks of the iron-bearing formation. The deposits, while large, are relatively insignificant with reference to the great adjacent masses of ferruginous cherts and jaspers making up the bulk of the formation. The percentage of iron ore to iron formation by weight to depths now mined, calculated from estimates of tonnage, is as follows:

TABLE SHOWING PROPORTIONS OF ORE TO IRON FORMATION IN THE LAKE SUPERIOR REGION

District:	Percentage of ore to iron formation by weight.
Marquette	0.110
Penokee-Gogebic	0.165
Menominee, Crystall Falls, and Iron River	0.183
Mesabi	2.00
Vermilion	0.062
Michipicoten	0.006

STRUCTURAL FEATURES OF OREBODIES.

It will be shown later that the iron ores are the result of surface alteration of the iron formations and are localized at places where these alterations have been most effective, particularly where the ordinary ground-waters are converged within the formation, due to various structural conditions. Because of this the ores are usually concentrated in the upper parts of the formation and always extend to the surface, though their extension in depth may be 2000 or more feet. It may readily be conceived that there are a great variety of structural conditions which determine the circulation of the altering waters and therefore the localization and shapes of the ore deposits within the formation. Such structural features are joints, faults, folds, intersection by igneous rocks, impervious sedimentary layers within or below the iron formation, and area of exposure. Description of the structural features of the ores is involved with detailed descriptions of the ores of the several districts, but some of the more salient features of the structural relations are summarized below.

The development of ore within the iron formation depending as it does upon accessibility of altering solutions from above, the largest access is given by wide area of exposure of the iron formation, which is in turn a function of the dip. The flat-lying Mesabi formation exposes a greater surface to concentrating agents than the steep-dipping Gogebic formation of similar thickness and character, with the result that the proportion altered to ore is much greater in the Mesabi district. A comparison of the actual areas of the different iron formations with their total shipments to date, and with their probable reserves, shows a close relation between area and amount of ore developed.

Of more immediate and practical importance in relation to the distribution of the ores are the structural conditions such as impervious basements and fractures, which determine the location of ores within a given area of iron formation. Impervious basements for the orebody may be formed: (1) by intersection of foot-wall quartzite with igneous dike, as in the Gogebic district; (2) by irregular intrusive masses of basic igneous rock, as in the Marquette district; (3) by dolomite, as in the Menominee district; (4) by slate, as in the lower horizons of the Negaunee formation in the Marquette, the Crystal Falls, Iron River, and Florence districts, and in the upper horizon of the Vulcan formation of the Menominee district;

(5) by slate layers within the iron formation, locally developed in the Gogebic and Mesabi districts; and (6) by granite, as in the Swanzy district of Michigan and very locally in the Mesabi district. Most of these basements have the configuration of pitching troughs.

The ores are likely to be closely associated with fracturing of the iron formation, giving access to altering solutions, particularly well illustrated by certain of the Mesabi deposits, by parts of the Gogebic deposits which pass through faults in the impervious basement, and indeed illustrated to a greater or less extent by practically all of the iron-ore deposits of the region.

The relative importance of the several structural features of the ore deposits varies widely from place to place. In the Gogebic district the existence of impervious basements in the form of pitching troughs seems to be the essential structural feature of the ore deposits. Localization of the ores within and adjacent to fissures in the iron formation is also apparent. On the other hand, in the Mesabi district the conspicuous feature is the localization of the ores by fractures in the iron formation, the impervious basement being so gently flexed as to make it difficult to ascertain whether or not it forms pitching troughs which control the localization of the orebody.

SHAPE AND SIZE OF THE OREBODIES.

Because of the wide variation in the structural features determining the development of an ore deposit, outlined under the preceding heading, the shapes of the deposits for the region are so various that they collectively may be designated by the word 'amoeboid', though there are several groups of more uniform shape, as described below. They may be roughly tabular in a horizontal plane, as in the Mesabi district, roughly tabular in steeply inclined planes, as in the Menominee district, linear, as in certain Menominee deposits, or almost any combination of these shapes.

The horizontal dimensions known at the surface range up to a mile, and, indeed, in the Hibbing area of the Mesabi district, the deposits are more or less connected for a distance of ten miles. The horizontal area would range up to two square miles. The maximum depth of mining at the present time is 2200 feet.

It is therefore apparent that the size, shape, and structural relations of the Lake Superior ores are in widest variety. In the flatlying Mesabi formation the orebodies have wide lateral extent as compared with depth, have extremely irregular outlines partly controlled by jointing, abut irregularly on bottom and sides against unaltered portions of the iron formation, and when the glacial overburden is removed, are accessible to surface operations with steam-shovels. Steep-dipping formations, comprising most of the formations of the districts other than the Mesabi, have greater vertical dimensions as compared with horizontal dimensions, usually abut not only against unaltered parts of the iron formation, but against well defined, impervious walls consisting of slate, quartzite, dolomite, or bosses or dikes of greenstone, and underground mining is necessary.

TOPOGRAPHIC RELATIONS OF THE OREBODIES.

The ore deposits are associated with hills or ranges, explaining the common use of the term 'range' in connection with the ore-producing districts. There are, however, exceptions to this relation in the Cuyuna district of Minnesota, and perhaps elsewhere. The ore deposits sometimes occur on the top of the hill, as in the Vermilion district, commonly in the middle slopes, well illustrated by the Mesabi district, and on the low ground adjacent to the hills, as in part of the Gogebic, Marquette, and Menominee districts. While in general the middle slopes seem to be favored, there are so many exceptions to this that there is no warrant for limiting prospecting to such localities. As the development of the orebodies is a function of the rapid circulation of waters from above, it is believed that the common association of the ore deposits with hills is due to the fact that there are places where the circulating waters are given considerable head. It would not follow that ore deposits should for this reason be confined entirely to the vicinity of hills, for circulation, perhaps less deep, seems to be effective in relatively flat areas, as in the Cuyuna district of Minnesota. The effectiveness of the head with different elevations and with different structural relations is not well known. Also, it is to be remembered that the concentration of the ore deposits has not taken place entirely in relation to present topography, but that when the ore deposits were concentrated, the topography was more or less different, and that, therefore, ore deposits now found independent of topographic elevations may still have been developed under control of an elevation which has since been removed. Notwithstanding these various limitations, to be considered in the interpretation of the relations of ore deposits to topography, the present prevalence of by far the greater number of ore deposits on the middle slopes of the ranges is extremely suggestive, for these are the places where the flow of meteoric waters directly from the surface should be at the maximum.

OUTCROPS OF OREBODIES.

By far the greater number of the Lake Superior ore deposits are softer than at least one of their walls. They therefore occupy depressions which are largely covered with glacial drift, and seldom outcrop. A few of the ores, such, for instance, as the hard ores of the Vermilion and Marquette districts, are nearly or quite as hard as the wall rock, have resisted erosion, and occasionally project above the mantle of drift. Considering the number of orebodies found in the Lake Superior region and their variety of structural relations, it is surprising that so few have been found to outcrop. The lean silicious and magnetic parts of the iron formation have withstood erosion to such an extent that they outcrop rather commonly. These, together with magnetic variations, have served as guides to the location of the iron formation, and have led to the discovery of ores in the low-lying areas by underground work.

Where the iron-ore deposits have their greatest dimensions on the erosion surface, the ratio of area of iron ore to area of iron formation is greater than the ratio of tonnage of iron ore to tonnage of iron formation. In the Mesabi district it runs up to nearly 8% for the producing part of the district. For most of the other ranges the ratio is far smaller, usually less than 1 per cent.

CHEMICAL COMPOSITION OF THE ORES.

The average composition of the iron ore of the Lake Superior region for the years 1906 and 1909 is calculated from the cargo analyses published by the Lake Superior Iron Ore Association of Cleveland, together with analyses of different mine grades furnished by individual mining companies. The averages are obtained by combining all grades in proportion to tonnage and the table represents more nearly the average composition of all of the ore mined in the Lake Superior region in any one year than anything before attempted. Analyses of iron ore used in other parts of this chapter are also taken from the Lake Superior Iron Ore Association tables.

AVERAGE COMPOSITION OF TOTAL YEARLY PRODUCTION OF LAKE SUPERIOR IRON ORE FOR THE YEARS 1906 AND 1909

	Per cent. 1906.	Per cent. 1909.
Moisture (loss on drying at 212°F.)	....	11.28

	Per cent. 1906.	Per cent. 1909.
Analysis of ore dried at 212°F.		
Iron	59.80	58.45
Phosphorus	0.0810	0.091
Silica	6.83	7.67
Alumina	1.60	2.23
Manganese }	2.70	0.71
Lime }		0.54
Magnesia }		0.55
Sulphur }		0.060
Loss by ignition	3.92	4.12

RANGE IN PERCENTAGE FOR EACH CONSTITUENT OF ORES MINED IN 1906 AND 1909, AS SHOWN BY AVERAGE CARGO ANALYSES.

	Per cent. 1906.	Per cent. 1909.
Moisture (loss on drying at 212°F.).	....	0.50 to 17.40
Range in composition of ore dried at 212°F.		
Iron	38.15 to 66.07	35.74 " 65.34
Phosphorus	0.008 " 0.850	0.008 " 1.28
Silica	3.21 " 40.97	2.50 " 40.77
Alumina	0.20 " 3.59	0.16 " 5.67
Manganese	....	0.00 " 7.20
Lime	....	0.00 " 4.96
Magnesia	....	0.00 " 3.98
Sulphur	....	0.003 " 1.87
Loss by ignition	0.00 " 10.0	0.40 " 11.40

The grade of ore shipped and its general uniformity for given districts and periods is in the last analysis controlled by the nature of the ores available, yet the commercial conditions to some extent determine the matter. For instance, with high, medium, and low-grade ores available, a period of financial depression may make it possible to ship only the highest grade ores, whereas business prosperity may make it possible to mix considerable quantities of lower-grade ores with higher-grade ores, thereby lowering the average grade. Further illustrating this control of commercial conditions, the acid Bessemer steel process for years determined that an unusually high proportion of low phosphorous ores should be shipped. The recent rapid development of the open-hearth process has allowed the shipment of ores containing more phosphorus. The development of the basic open-hearth process is ultimately based on the availability of large reserves of high-phosphorus ore, but in turn the development of the open-hearth reacts upon and determines the grade of ore shipped from any district or for any period.

MINERALOGY OF THE ORES

The minerals of iron ores in general are as follows:

1. Magnetite: Magnetic oxide, Fe_3O_4, including titaniferous magnetite. Theoretical iron content of the pure mineral, 72.4%. Generally containing some hematite.
2. Hematite: Anhydrous sesquioxide, Fe_2O_3, including specular hematite, red fossil ore, oölitic ore, etc. Theoretical iron content of the pure mineral, 70 per cent.
3. Brown ore: Hydrous sesquioxide, $Fe_2O_3 . nH_2O$, including turgite, limonite, gothite, or a mixture of these minerals, known locally as brown hematite, bog ore, gossan ore, etc. Theoretical iron content of iron minerals, 59.8 to 66.2%, depending on degree of hydration.
4. Carbonate: Siderite, iron carbonate, $FeCO_3$, known locally as spathic ore, black band ore, etc. Theoretical iron content of the pure mineral, 48.2 per cent.

The Lake Superior iron ores are (1) soft, brown, red, slaty, hydrated hematites; (2) soft limonite; (3) hard massive and specular hematites; (4) magnetites; and (5) various gradations between (1), (2), (3), and (4). The proportions for the entire region of these different classes shipped in any one year, 1906, for example, as calculated from average analyses, are as follows:

TOTAL PRODUCTION BY GRADES FOR 1906.

Class of ore.	Tons.	Per cent of total
Soft, brown, red, slaty, hydrated hematite.......... Soft limonite ores	35,652,174	93
Hard massive and specular hematite............... Magnetite (less than 1% included with hard ores)..	2,741,323	7
	38,393,497	100

The approximate mineral composition of the average ore of the entire district for the years 1906 and 1909, calculated from the average analyses, is as follows:

APPROXIMATE MINERAL COMPOSITION OF AVERAGE ORE FOR 1906 AND 1909 CALCULATED FROM AVERAGE CARGO ANALYSES.

	1906. Per cent.	1909. Per cent.
Hematite* more or less hydrated) with some magnetite ($3Fe_2O_3H_2O$)	88.60	86.45
Quartz	4.53	4.89
Kaolin	6.87	5.25
Chlorite (and other ferro-magnesian silicates)........		1.01
Dolomite		0.81
Apatite (all phosphorus figured as apatite)........		0.48
Miscellaneous	...	1.11
	100.00	100.00

*The iron minerals may be expressed in terms of hematite and limonite as follows: 1906, hematite 66.60%, limonite 22.00; 1909, hematite 66.75%, limonite 19.70. These minerals do not in fact exist in these proportions, there being a number of hydrates between hematite and limonite.

The above mineral compositions are necessarily only approximate, as ferric and ferrous iron are not separated in the chemical analysis, and water, carbon dioxide, and possibly a small amount of organic matter, are all included under loss on ignition.

In the above table are mentioned the abundant minerals associated with the iron: quartz, kaolin, and carbonate. Many of the minerals termed miscellaneous in the table are present in limited amounts and with limited distribution. Some of these minerals are apatite, adularia, wavellite, calcite, dolomite, siderite, pyrite, marcasite, chalcopyrite, tourmaline, masonite, ottrelite, chlorite, mica, garnet, rhodochrosite, manganite, pyrolusite, barite, gypsum, martite, aphrosiderite, analcite, goethite, and turgite.

While many of the Lake Superior ores are slightly magnetic, there are only two mines in the region, the Republic and Champion, which ship ores classed as magnetite ores, and even these ores are largely specular hematite with large quantities of magnetite. There are in the region, however, large quantities of lean non-titaniferous magnetic iron formation, as at the eastern end of the Mesabi range and the Gunflint district, where the Duluth gabbro cuts and overlies the formation, both the eastern and western ends of the Gogebic range, where Keweenawan intrusives cut the formation, and in parts of the Marquette district, although on the last-named place the effects of the intrusion may not all be discriminated from those of close folding.

The magnetite ores are coarse-grained magnetite-quartz rock carrying a considerable variety of metamorphic silicates, including amphiboles, pyroxenes, garnets, chlorites, olivines, cordierite, riebeckite, dumortierite, etc. Locally pyrite, pyrrhotite, and iron carbonate are present. The minerals show greater variety and more complex chemical constitution than those of other phases of the iron formation. Where altered at the surface, the magnetite may be locally coated with limonite and the silicates may have gone over to chlorite, epidote, and calcite. The yellowish-green colors so developed are extremely characteristic of the surface.

PHYSICAL CHARACTERISTICS OF THE ORE.

The ores range from the massive and specular hematite and magnetite through ores which are partly granular and earthy, and partly in small hard chunks, to ores that are almost entirely soft and earthy. There is no very sharp difference between the hard ores and the soft ores. The latter make up the great bulk of the annual shipments. For 1906 fully 93% would be classed locally as soft ores. The principal hard ores come from the Vermilion district and from the upper horizons of the Negaunee formation in the Marquette district. The soft ores commonly contain small hard chunks usually bounded by parallelopiped faces due to being broken up in the bed by minute joints. Screening figures from the Mesabi indicate the texture of the typical soft ore. There is a striking contrast in the coarse texture of the magnetite ores and the fine cherty textures of the other phases of the iron formation. The quartz grains in the jaspers of the eastern part of the Marquette district average from 0.01 to 0.03 millimetres, whereas in the west and southwest portions of the same district in the amphibole magnetite phases of the formation the quartz grains average about 0.1 to 0.4 millimetres and run as high as 1 millimetre. The quartz grains of the amphibole magnetite rocks may thus have a million times the volume of those of the jaspers. The quartz grains near the gabbro in the eastern part of the Mesabi district reach a diameter of 3 or 4 millimetres, while in the central and western portions of the district they are seldom greater than 0.10 millimetre. In a given amphibole magnetite rock the grains are fairly uniform in size and have a tendency toward polygonal shape, whereas in the other parts of the formation they are most irregular in size and shape, and show the characteristic scalloped boundaries of cherts.

The mineral density of the ores ranges from less than 3.5 to 5.0, and averages about 4.30; the pore space from 1% to 60%, averaging about 35%. The free moisture held in this pore space ranges from 0 to 16%, and averages about 10.42%.

The cubic dimensions of a ton of ore range from 7 cubic feet for the hard ores to 14 cubic feet for the soft ores.

ORIGIN OF THE ORES OF THE LAKE SUPERIOR PRE-CAMBRIAN SEDIMENTARY IRON FORMATIONS.

In considering the origin of the iron ores of the Lake Superior sedimentary type, the observer is first impressed with the variety and abundance of evidence for the secondary concentration of the ore. Whatever the ultimate nature and source of the sediments, the observer is left in no doubt that the iron ores owe their present characters to the concentrating agencies of the atmosphere and hydrosphere, which can be seen in operation today. This surface concentration will be first discussed to clear the way for consideration of the primary nature and source of the iron formation, though this means departure from strict chronological sequence.

SECONDARY CONCENTRATION OF THE ORES.

General Statements.—The secondary alteration of the iron formation to ore has been both chemical and mechanical, and under conditions of weathering, on the one hand, or folding and deep burial and proximity to igneous intrusions on the other. The essential changes in the development of the ores have been effected under weathering conditions. The ores once formed, alterations effected by dynamic action, igneous intrusion or redeposition as fragmental sediments may be regarded as for the most part subsequent and modifying factors tending to change somewhat the character of the ores and ore deposits, but adding little to their size or richness. Dynamic and igneous metamorphism acting before the concentration of the ores tends to inhibit ore concentration by making the iron formation resistant to weathering, as emphasized below.

Chemical and Mineralogic Changes Involved in Concentration of the Ore Under Surface Conditions.—It requires only the most general field observation to bring out the fact that the iron formations are being and have been rapidly altered by percolating waters carrying oxygen, carbon dioxide, and other constituents from the surface, and that the present characteristics of the formation are considerably different from those of the same formations when they first became dry land. Now they consist mainly of ferruginous chert and jasper with subordinate quantities of iron ore, paint rock, greenalite, iron carbonate, amphibole magnetite rock, etc. Formerly the formations were more largely cherty iron carbonate or greenalite. Fortunately, the alterations have not everywhere gone far enough to obliterate all of the original phases of the iron formation. Gradations may be observed between original cherty iron carbonate or greenalite phase of the formation and the dominant alteration products, ferruginous cherts and jaspers and iron ores. The former are found in protected places beneath slate or other impervious cappings, while the latter are in portions of the formation exposed to percolating oxidizing waters. The former are ferrous compounds unstable under surface weathering conditions, and the latter are the stable oxides, end products of weathering. The ferruginous cherts, jasper, and iron ores, furthermore, retain textures characteristic of carbonate and greenalite, thereby betraying their derivation from these substances. This is especially noticeable in the ores and cherts derived from greenalite, the peculiar granular shapes of the greenalite being conspicuous in their derivatives. The red, brown, and yellow colors of the altered phases of the formation, the ores, and ferruginous cherts, contrast strongly with gray and green or the original cherty carbonate and greenalite, making the alterations conspicuous, especially along fissures in the original rocks.

The secondary alterations of iron carbonate and greenalite rocks to iron ore involve: (1) Oxidation and hydration of the iron minerals in place; (2) leaching of silica, and (3) introduction of secondary iron oxide and iron carbonate from other parts of the formation. These changes may start simultaneously, but (1) is usually far advanced or complete before (2) and (3) are conspicuous. The early products of alteration therefore are ferruginous cherts, that is, rocks in which the iron is oxidized and hydrated and the silica not removed. The later removal of silica is necessary to produce the ore. Change (3), the secondary introduction of iron oxide and iron carbonate in cavities left by the leaching of silica, is of little importance in the alteration of the greenalite rocks to ore. In the alteration of the carbonates to ore it is frequently a conspicuous feature. The alteration of the original iron formation rocks to ore may therefore be treated under two main heads: (1) Oxidation and hydration of greenalite and siderite producing ferruginous chert, and (2) alteration of ferruginous chert to ore by leaching of silica, with or without secondary introduction of iron.

Oxidation and hydration of the greenalite and siderite producing ferruginous chert.—The oxidation of the cherty iron carbonates and greenalites to hematite or limonite, produces ferruginous cherts of varying richness. During these changes the iron minerals, for the most part, are altered in place, but iron may also be transported and redeposited. Evidence of this is abundant in the stalactitic and botryoidal ores lining cavities or encrusting secondary quartz crystals and numerous veins of ore cutting across the bedding of the formation. It has been shown quantitatively[2], however, that the principal enrichment of the ore takes place in connection with the removed silica, although in several districts the introduction of iron is very important. The oxidation and hydration of the original iron minerals are expressed in the following reactions:

$$4FeCO_3 \text{ (siderite)} + nH_2O + 2O = 2Fe_2O_3.nH_2O + 4CO_2$$

$$4Fe(Mg)SiO_3.nH_2O \text{ (greenalite)} + 2O = 2Fe_2O_3.nH_2O + 4SiO_2$$

[2]Mon. U. S. Geol. Surv., 52, 1911, cit.

The alteration of the iron minerals is facilitated by small amounts of acids carried by percolating waters. Carbonate of iron is difficultly soluble in pure water, and not easily soluble with an excess of carbon dioxide. On the other hand, it is easily soluble in either of the stronger acids, sulphuric or hydrochloric. Sulphuric acid results from the decomposition of the iron sulphide in the original carbonates and in the adjacent pyritiferous greenstones and slates. The reaction may be:

$$FeS_2 + H_2O + 7O = FeSO_4 + H_2SO_4$$

This is aided in turn by carbon dioxide in the water. Thus the iron sulphide is oxidized to ferrous sulphate with simultaneous production of sulphuric acid, which attacks the iron carbonates and changes them to soluble ferrous sulphate. In the Michipicoten district, where glacial erosion has cut deep, sulphides are found abundantly with the carbonates. Sulphate of iron is present in veins in the ores of the Iron River district. W. S. Bayley[3] found the white efflorescence characteristic of Menominee ores to be essentially sodium sulphate with formula of Glauber salt, $Na_2SO_4 + 10H_2O$, which he regards as the result of decomposition of pyrite and muscovite. Iron sulphides and chalcopyrite are also common as vein fillings. Sulphates are found in mine waters. Humus acids are also well known to aid in the solution of the iron.

Precipitation of the iron from ferrous solutions may be caused (1) by direct oxidation to limonite, or (2) by reaction with alkaline carbonate, producing iron carbonate, which in this form in the presence of oxygen alters almost immediately to hydrated iron oxide, or (3) by loss of carbon dioxide. A small amount of secondary iron carbonate, where iron is carried in solution as bicarbonate, observed locally in each of the districts, is incidental to the main process of oxidation producing ferruginous cherts.

The oxidation of the iron in the carbonate and greenalite goes on much more easily and rapidly than the removal of the silica, and may affect most or all of the carbonate or greenalite, producing ferruginous cherts, before the removal of the silica has gone far enough to be appreciable. An epitome of the story for the formation is told by almost any hand specimen of iron carbonate or greenalite. The ferruginous cherts are, therefore, intermediate phases between the original greenalite or siderite and the ore, and the principal removal

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[3]'Menominee Iron-Bearing District of Michigan,' by W. S. Bayley. Mon. U. S. Geol. Surv., 46, 1904, pp. 390-391.

of the silica is subsequent to the formation of the ferruginous cherts. Given sufficient time and the other necessary favorable conditions, and any part of them may become ore. In districts where greenalite is the dominant original iron compound, so far as can be determined, the layers of chert in the ferruginous cherts prior to their alteration to ore are not far different in number, thickness, iron content, or degree of hydration, from those in the greenalite rocks, indicating but little transfer of iron, though locally the segregation of silica and iron oxide into bands is more accentuated. In districts where carbonate is an important original iron salt, the rearrangement, transportation, and introduction of iron salts are quantitatively important. Slight rearrangements of the iron ore are to be seen in the concretions composed of alternate concentric layers of chert and iron oxide developed during the alteration. These develop both from the iron carbonate and the greenalite.

Alteration of ferruginous chert to ore by leaching of silica, with or without secondary introduction of iron.—Ore may be formed: (1) by taking away silica from the ferruginous cherts, leaving the iron oxide; (2) by taking out silica and introducing iron in its place; or (3) by adding iron to an extent sufficient to make the percentage of silica a small one. In the latter case there would necessarily be large increase in volume. Quantitative tests show that (1) is of greatest importance, that (2) is effective only in some of the ores derived from carbonates, and that (3) is practically negligible.

Measurements of pore space of the ores derived from the alteration of ferruginous cherts of greenalitic origin bring out the fact that pore space approximates the volume of silica which has been removed, though it is a little less on account of slump observed in the ore layers; in other words, the filling of the pore space in the ores by silica would nearly reproduce the composition of the ferruginous cherts. It will be shown also that the leaching of silica from the ferruginous cherts derived from greenalite alterations does not materially affect the character of the iron oxides, especially their degree of hydration, and that therefore the nature of the ore of the deposit is primarily determined by the changes which the greenalite undergoes when it alters to the oxide bands of the ferruginous cherts.

Measurements of pore space in ores derived from ferruginous cherts which in turn have been derived from the alteration of iron carbonate show the pore space is less than the volume of the silica which has been removed. This is due partly to slump, but mainly to the fact that secondary iron oxide partly fills the openings.

Silica dissolved from the iron formations has been in small part redeposited in veins both in ore and rock and in the crystallized quartz linings of many cavities in the ore, and in part has joined the run-off. The process is going on today, for mine and surface waters carry silica, and quartz linings of cavities may be seen to have developed since mining explorations began. It has been suggested that the abundant chert in the ferruginous cherts themselves might represent materials previously leached from other parts of the formations and redeposited. As the cherts are very dense, there would be no room for the addition of secondary silica except that made by the volume change in the alteration of iron minerals or by the previous leaching of silica. Undoubtedly cavities of both sorts have been filled to a certain extent by silica; but the process of the average increase of silica would involve a reversal of the one which is actually observed to occur, that is, the leaching of silica from the ferruginous cherts producing the ores. It seems clear that while, as in any metamorphic process in the belt of weathering, silica is removed and silica is deposited, the former is predominant. A parallel may be cited in development of caves in limestone by solution and deposition, the process of solution predominating.

Effect of Variation of Iron Content in Original Rock on Secondary Concentration.—The foregoing discussion takes no account of great variations in richness of the various phases of the iron formation. It is obvious that where there are exceptionally rich beds, less secondary concentration is required to produce a high-grade ore than in originally leaner parts of the formation. One of the questions of practical significance in exploration is the extent to which the iron ores are actually confined to portions of the formations that were originally rich in iron. In certain districts there are known rich zones of iron formation in which exploration is likely to yield good results. But in general the evidences of secondary concentration have so masked the original character of the iron formation that its originally rich portions cannot be accurately delimited. It might be further asked whether any deposits represent parts of iron formation originally so rich that secondary concentration has had relatively little effect in producing the iron ore. There is a possibility that certain of the more massive iron ores of the Keewatin formation, which have been so thoroughly anamorphosed as to obliterate evidences of their original character and of their secondary concentration, may have been of this type, but in the absence of direct evidence this can only be cited as a possibility.

Secondary Concentration of the Ores Characteristic of Weathering.—Quartz is ordinarily regarded as practically insoluble in surface waters. It might be argued that the conditions above cited are not peculiar to iron formations alone, but may be found elsewhere, and the question is raised whether elsewhere quartz is largely taken into solution. It is believed that quartz is taken into solution under ordinary weathering conditions to a larger extent than is generally recognized, and that it is apparently stable because it is usually associated with more soluble constituents, thereby contrasting with the iron formations where the quartz is associated with less soluble constituents against which the loss of quartz may be measured. A series of three analyses of fresh granite, partly altered granite, and much weathered granite from Georgia, published by T. L. Watson,[4] when recalculated in terms of minerals, shows that in the early stages of the alteration the quartz is but little affected, but that in the last stage there is unquestionable evidence of considerable leaching of free quartz. In general, comparison of analyses of various fresh and weathered igneous and other rocks shows that iron and alumina are the two most stable constituents, and that silica is lost more readily than the iron. The iron formation, consisting principally of iron minerals and silica, and lacking alumina, would therefore be expected to retain its iron under weathering to a greater extent that the silica, and in so doing has followed the general laws of katamorphism. The absence of evidence of transfer of iron during secondary concentration is in strong contrast with its abundant transportation in the primary sedimentation. The secondary local transfers of iron in the ferrous condition before it is oxidized to the stable form are characteristic alike of both the iron formation and igneous rocks and do not disprove the general principle above stated.

Mechanical Concentration and Erosion of Iron Ores.—There is little evidence of the mechanical concentration of the iron ores. Such ore as may have been concentrated at the surface by this method has been largely scraped off by the glaciers. However, so far as pore space has been lessened by mechanical slump, anywhere through the formation, this amounts to mechanical concentration

[4]'Granites and Gneisses of Georgia,' by Thomas L. Watson. Bull. Geol. Survey of Ga., No. 9A, 1902, p. 302.

of the iron ore. Locally, as at the base of the Vulcan formation in the Menominee district, at the base of the Goodrich quartzite in the Marquette district, and in the Cretaceous of the Mesabi district, there is fragmental detritus derived by the processes of disintegration, transportation, and sedimentation from earlier formed iron formations. Where this includes sorting, it amounts to mechanical concentration.

Other Factors Modifying Secondary Concentration.—Lack of space forbids discussion of a number of other interesting features of secondary concentration. I may merely note the fact, which may be inferred from description of the ore deposits, that this secondary concentration has been localized by a considerable variety of structural and topographic conditions. Before or after the second concentration some of the iron formations have been extensively modified by mechanical deformation or by igneous intrusions, with contact effects such as to prevent concentration of important iron ore deposits. The sequence of events varies for different parts of the region. Where, as in the Marquette district, there are two iron formations with successive orogenic and igneous episodes, the local history of the development of the ores becomes a complex one.

THE ORIGINAL NATURE AND SOURCE OF THE IRON FORMATION SEDIMENTS.

Before secondary concentration began, the iron formation consisted dominantly of cherty iron carbonate and iron silicate (greenalite), with minor amounts of banded iron oxides and cherts and of mud, sand, and gravel. The iron seems to have been dominantly in the ferrous form, but with some ferric oxide; the relative proportions of these two cannot be definitely fixed for parts of the region. That these rocks are sediments admits of no doubt. They are bedded and locally cross-bedded and interlayered with other sediments. The conditions which allowed of the deposition of the iron formation sediments, ranging up to the unique thickness of 1000 ft., present a problem which requires consideration of a wide range of factors.

Iron Formation Mainly a Chemical Sediment.—The iron formations are regarded mainly as chemical sediments: (1) because they originally consisted of iron carbonate and ferrous silicate and possibly some iron oxide, similar to substances known elsewhere to be deposited as chemical sediments; (2) because they may be synthesized in the laboratory by the simple chemical reagents which were probably present where the iron formations were formed; and (3) because they usually lack fragmental particles; to a minor extent they are fragmental formations derived from the erosion of earlier iron-bearing and other formations.

Are the Iron Formations Terrestrial or Subaqueous Sediments?—It is believed that the iron formations are subaqueous for the following reasons:

1. They originally were ferrous compounds. Terrestrial sedimentation usually produces ferric oxides—hematite or limonite and laterite, except in bogs, and reasons are advanced elsewhere to show that only a part of the Lake Superior iron formation may be so developed.

2. The middle and upper Huronian iron formations are parts of sedimentary groups containing quartzites and slates of probable subaqueous origin.

3. The iron formations in the Keewatin have not been found deposited in erosion channels of the underlying rocks. They rest conformably upon them without intervening weathering or erosion.

4. All of the iron formations are associated with basalts with conspicuous ellipsoidal structures, which can be best explained as developed by flowing out in water. They contrast in this regard with basic lavas of the Keweenawan.

Possibility of Bog Origin.—Several facts suggest the possibility of something in the nature of a bog origin for the sediments. The bog theory of origin involves the assumption that the Lake Superior region may have been covered by great bogs or lagoons during each of the iron-depositing periods, in which vegetal matter could grow at or near the surface of the water over great areas, such as in lagoons in advance of barriers thrown up by the sea encroaching over a gently sloping surface, or under delta conditions. As a process necessarily confined to a shallow zone near the surface, its continuous operation would involve continuous and uniform subsidence at a rate commensurate with the deposition of the iron salts in order to produce the thicknesses now known. While probably applicable to some of the thin lenses of small extent associated with carbonaceous slates, it is not clear how this process could produce a thousand feet of iron formation sediments with uniformity of lithology and bedding without extraneous material through many hundreds of square miles. Other arguments against bog origin are available in the greenalitic character of the iron formation itself and in its association.

Iron Formation Sediments Apparently Not the Results of a Normal Cycle of Erosion of Average Land Surfaces. –The following facts seem to indicate a derivation of part of the iron formations through some process other than weathering of ordinary land surfaces.

1. On the assumption that the iron formations have been derived from weathering of average land areas it has long been recognized that there were difficulties in the way of explaining the thick and uniform masses of chemical sediments constituting the thicker iron formations, accompanied by so little mechanical sediment. For instance, if the peculiar character of chemical sediments depends upon depth of water and distance from shore, then the great thickness of the formation involves uniform subsidence over a great area to keep the conditions uniform. Even this would not explain the absence of ordinary fragmental sediments.

2. The iron formation sediments are richer in iron than average of even basic land-surfaces from which they might have been derived. When the abundant fragmental sediments associated with the iron formations are figured in this calculation, it appears also that the series which includes the iron formation contains an excess of iron.

3. If it be regarded as possible that the source of the iron formation is in weathering of ordinary land surfaces, why should the iron formations not be reproduced on the same scale in the Paleozoic which was deposited on pre-Cambrian rocks similar to those beneath the iron formations? The deposition of the Paleozoic was preceded by perhaps the longest period of weathering of which we have record in the Lake Superior country. Paleozoic and later sediments contain in various parts of the United States thin beds of sedimentary iron formation material, but these beds are at their maximum insignificant in thickness as compared with those of the Lake Superior region. For instance, the thickest known iron carbonate bands are 8 to 10 ft. in the Carboniferous, while in the Lake Superior region carbonates reach 800 ft. over large areas.

4. The surface streams are only locally carrying iron in quantity at the present time. All available analyses of river waters show a lack of iron with the exception of minute quantities in the Ottawa and St. Lawrence rivers. While the springs frequently carry iron, this is conspicuously deposited at the point of escape and does not join the run-off. These facts are correlated with known observations of the manner of weathering of rocks. The iron be-

comes oxidized and, next to alumina, is the most stable under surface conditions. As compared with alumina so little is lost that G. P. Merrill, T. L. Watson, and others have used both iron and alumina as a basis against which to measure loss of other constituents.

It appears, then, from the foregoing, that there are objections to regarding the iron formations entirely as sediments produced by weathering of the rocks most abundant in the adjacent lands. In character and size the iron formations are unique as chemical sediments, and differ from other chemical sediments derived by normal weathering processes. Some unusual factor seems to be required to explain them. Such a factor is discussed under the following heading.

Character and Abundance of Iron Formation Sediments Believed to Be Explained by their Association with Abundant Basic Igneous Rocks.—To make a long story short, the iron formation sediments are believed to owe their unique features to association with vulcanism. This is a view of origin which differs from that formerly held. It has been forced upon us gradually, not only because of the difficulties of explaining the iron formation sediments as developments under ordinary conditions of sedimentation, indicated on previous pages, but by the positive evidences of genetic relationship which may here be only mentioned. Many localities might be cited where the iron formation sediments constitute bands between successive flows of basalt, where abundant iron salts have separated out in the basaltic magma itself, and where the basalt grades through tuffaceous phases into the iron formation. The slates, with which the iron formation is characteristically associated, have a peculiar character, indicating probable derivation from basic igneous rocks. Each of the three periods of deposition of the iron formation was also a period of basic volcanic extrusion, characterized by ellipsoidal structure, of probable submarine origin. Other periods through this region not marked by the deposition of iron formation are also not marked by the deposition of ellipsoidal basalts. The association of iron formation sediments and basic igneous flows is repeated in many parts of the world. It is exceptionally characteristic where basalt flows have developed the ellipsoidal structure, which has been regarded by those who have studied these basalts as of probable subaqueous origin.

Evidence of the type above indicated seems to us to show beyond reasonable doubt that there is some sort of a genetic relationship between the iron formation and igneous rocks, but concerning the specific nature of this genetic relationship we are not prepared to speak definitely. There is a great variety of evidence bearing on the problem, and it is possible to reach definite conclusions only for certain parts of the region. For the region as a whole, however, the situation may be summarized by the statement that the iron salts of the basic extrusives have become available for concentration as iron formation sediments: (1) So far as the basic igneous rocks arose above the water, through the agency of weathering with the aid of organic material and the residual heat and vapors of the igneous rocks; (2) by direct contribution of hot solution by igneous rocks to the water in which the iron formation was laid down; (3) by some combination of (1) and (2).

That weathering of basic igneous rocks, especially when hot, would yield sediments rich in iron requires no extended argument. Both field and laboratory investigations show that all types of Lake Superior iron formation known can result directly from alteration of this kind. This applies even to the greenalite, which we have succeeded in synthesizing in the laboratory from sulphate solutions of the type which certainly were derived in some amounts from the igneous rocks.

That any part of the iron formation sediments was the result of direct contribution in hot solutions by igneous rocks is not likely to be so readily accepted, and in fact is one for which specific evidence in the nature of the case is less satisfactory. Some of the considerations which lead us to believe that direct contribution may play some part in furnishing the materials for the iron formation sediments are these: The igneous rocks are rich in iron and contain concentrations evidently deposited from magmatic solutions late in the cooling of the mass. Veins of sulphide and iron oxide cements around ellipsoidal blocks, pegmatitic and other segregations of iron within the mass, all point to the fact that any solutions which escaped from these masses were rich in iron. If the evidence be accepted that the ellipsoidal blocks are the result of subaqueous cooling, and if the iron formation has been developed at all from its closely associated ellipsoidal flows, it must be by some processes other than subaerial weathering. The frequent absence of any normal sediments from the iron formation further suggests this possibility. Laboratory experiments show that there is nothing chemically improbable in the direct subaqueous contribution from the igneous rocks of iron and silica, and the remarkably close association and even apparent merging of iron formation and basalts rich in iron and silica is a fact which finds its readiest explanation by this hypothesis. It is even possible that there was direct reaction between the sea waters and the hot lavas. It has been possible in the laboratory to produce banded greenalite and chert rocks from reactions which are very suggestive of this combination of hot lava and salt water. The sharp contacts of iron formation rocks, the great thickness and general lack of contained mechanical detritus in the iron formation, notwithstanding its association with mechanical deposits, leads us to believe that the deposition of the iron formation sediments began suddenly and went on rapidly. It is not easy to conceive of the total inhibition of the deposition of fragmental sediments during this time, but relative rapidity of the deposition of the iron salts would mask the fragmental deposition. This rapidity of deposition would be more in accord with the hypothesis of rapid direct contribution of iron salts following igneous outbreak than their more slow accumulation through normal erosion processes of igneous rocks, and especially does this seem likely to be true where the iron formations completely lack associated fragmental material and are bounded both above and below by ellipsoidal flows.

We shall have no fault to find with the reader who refuses to accept as conclusive these arguments for direct contribution of iron salts from the magmas to the seas in which they were deposited as sediments. They do not amount to proof. We believe, however, that most geologists who study on the ground the intimate and varied associations of the iron formation and igneous rocks will give this hypothesis, as we do, serious consideration.[5]

CONCLUSION AS TO THE ORIGIN OF THE LAKE SUPERIOR IRON ORES.

The iron ores are results of secondary concentration of iron-rich portions of chemically deposited iron formations. The precise nature and conditions of this secondary concentration may be worked out on a quantitative basis. The sediments originally were cherty iron carbonates, greenalite and chert, and banded iron oxide

[5]There has been received too late for discussion a paper on British pillow-lavas and the rocks associated with them, by Henry Dewey and John Smith Fleet (*Geol. Mag.*, Vol. 8, Dec. 5, 1911, pp. 202-209 and 241-248), emphasizing the genetic association of cherts and ellipsoidal basalts. Albitization of the feldspars of the basalts is regarded as evidence of pneumatolitic emanations, containing soda and silica in solution, and possibly other substances. The cherts are deposited by those emanations. This independent conclusion is remarkably in accord with the inferences drawn in this chapter.

and chert, relative proportions of which remain to be definitely determined, but the first two of which are known now to be important. The iron formation sediments cannot be regarded as the results of a normal cycle of erosion of an ordinary land surface. Their characteristic association with ellipsoidal basalts suggests genetic relationship and offers plausible explanations for some of the unusual features of the iron formation. The specific manner and derivation of the iron formation sediments from associated igneous rocks is not clear, but seems to us probably to involve processes ranging on the one hand from those of ordinary weathering to an extreme of direct contribution of juvenile solutions to the waters in which the iron formation sediments were deposited.

FLATS AND PITCHES OF THE WISCONSIN LEAD AND ZINC DISTRICT.

By H. Foster Bain.

INTRODUCTION.

The Mississippi Valley north of the Gulf Plains and south of the Lake Superior region is a great area of flat-lying, unaltered Paleozoic sediments, which to the west pass under the Red Beds and Cretaceous sandstones of the Great Plains. To the east the valley is bounded by the Appalachian mountains, which are made up of rocks of the same age, but are structurally independent; a difference which dates from the Permian orographic revolution. The valley itself is practically free from important deformation, dips being measurable in metres per kilometre rather than in degrees. The prevailing rocks are dolomites, limestones, shales, and sandstones. Coarse sediments are almost entirely absent. The beds were laid down under shallow water conditions with concomitant leaching of the low-lying, pre-Cambrian, crystalline rocks which nearly surround the area. The region contains scarcely any later intrusive rocks, a few dikes only being known. Throughout geologic history it has acted as a unit, and since Paleozoic time, has been subjected to prolonged erosion at low altitudes. Neglecting the Ouachita mountains of southwestern Arkansas, which belong structurally with the Appalachians, the only important deformation areas are, (1) the Ozark uplift, an extensive, low, broad, elliptical dome, whose present elevation presents a slight warping of the Cretaceous peneplain, and (2) the Wisconsin uplift, a similar warped area. In both instances the uplifts include pre-Cambrian rocks, which seem to have formed islands through much of the Paleozoic, and to have furnished the bulk of the material now represented in the flanking sediments. The old lands to the east, south, and possibly to the west, also contributed. While there were frequent shiftings of the shore-line, conditions seem to have remained much

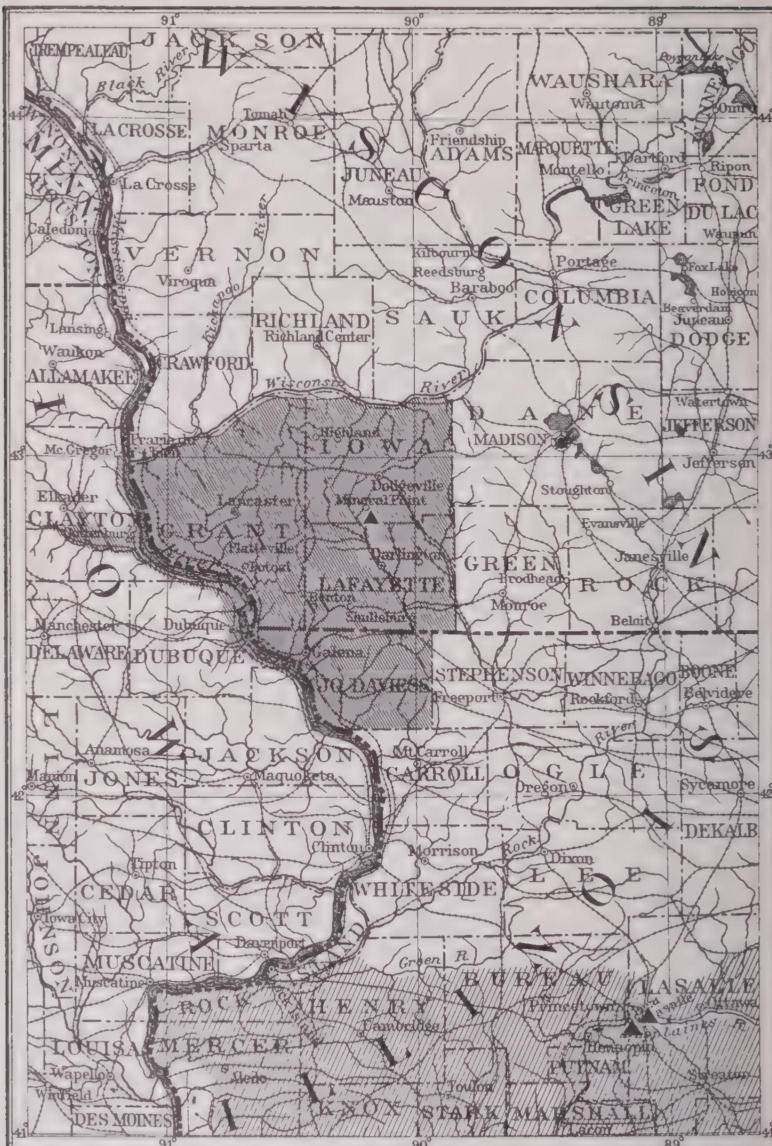
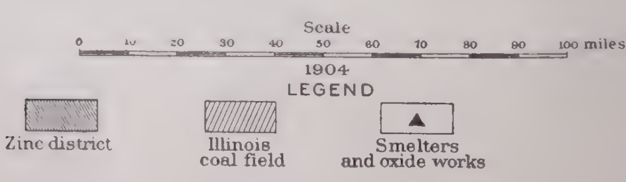


FIG. 1. MAP SHOWING RELATIONS OF ZINC DISTRICT TO COALFIELD AND SMELTERS.



the same from the Middle Cambrian to the Permian, the area being occupied by a shallow semi-enclosed marine basin, surrounded by low plains of crystalline rocks which contributed largely by solution and secondarily by corrosion to the slowly forming sediments.

The importance of this region as an ore-producing district is not always properly appreciated. Neglecting altogether the Lake Superior district, the Ouachita mountains, and the early iron output from the coal measures, and taking into account only the lead and zinc ores, there is still a recorded production up to the end of 1907 which, valued at local prices, has amounted to $337,000,000. Of this the value of the lead ore was approximately $200,000,000. If the record were to be made complete, something would need to be allowed for the copper ores of Missouri and Wisconsin, the manganese of Arkansas, the nickel and cobalt from Mine La Motte in Missouri, a little for silver from the Einstein mine in the pre-Cambrian rocks of the same State, a trifle for gold from placers in the drift of Indiana, and considerable for scattered iron deposits in Missouri, Iowa, Illinois, Indiana, and Wisconsin. It is evident that these totals are important and that the valley deserves to rank among the major mining regions of the world. Production has centred mainly in three areas: (a) Southeastern Missouri, which has yielded lead, iron, and copper; (b) southwestern Missouri and adjacent portions of Kansas, Indian Territory, and northern Arkansas, which have yielded zinc and lead; (c) southwestern Wisconsin, including portions of Illinois and Iowa, and having a recorded production of lead and zinc amounting to approximately $65,000,000. Mining in all of these districts is still active, despite the fact that operations began in 1719. The character and origin of the deposits found in this region has been much discussed. It is not my purpose to review here the whole subject. In another chapter of this book, E. R. Buckley has given a description and interpretation of the zinc and lead deposits of the Ozark region. My own paper will be confined to a description of the corresponding deposits of the upper Mississippi Valley, and specifically to the 'flats and pitches', a unique form of orebody characteristic of the Wisconsin district.

GEOLOGY OF THE DISTRICT.

The ore deposits here described occur on the southwest flank of the Wisconsin uplift. No corresponding deposits are known in eastern Wisconsin, though the formations are similar and the opportunities for secondary concentration equally favorable. The mining district is within a driftless area, surrounded by drift-covered plains. The ores occur in the Platteville limestone and the Galena dolomite; formations of mid-Ordovician age, corresponding roughly to the Trenton of eastern United States. The mines are not deep, 30 to 60 metres, and the ores have nowhere been mined more than a few metres below water-level. In form the orebodies are peculiar. Above water-level the deposits occupy small crevices, for which J. D. Whitney coined the term 'gash veins'.[1] In these crevices they form horizontal ore-shoots or runs, known locally as 'openings'. Below, the vertical crevices give way to horizontal flat openings between bedding planes, connected by pitching joints. These are known as 'pitches' and 'flats'. In the crevices, above water-level, galena and zinc carbonate are the common ores. In the pitches and flats the ore consists of blende, galena, and marcasite, intimately intergrown or in alternate layers or crusts. The region is a dissected peneplain fringed to the south and west by a scarp rising some 200 ft. above, and dotted with mounds, or monadnocks, of approximately the same height. (Fig. 2.) A general section of the rocks present in the region is given below.

System	Formation		Character	Thickness in Feet
Quaternary			Alluvium Terrace deposits Loess Residual clays	5 to 70
Silurian	Niagara		Dolomite	150
Ordovician	Maquoketa Galena Platteville St. Peters		Shales Dolomite Limestone and dolomite Sandstone	160 240 55 80
	Prairie du Chien	Shakopee New Richmond Oneota	Dolomite Sandstone Dolomite	50 10 to 40 200
Cambrian	'Potsdam'		Sandstone with minor shale and dolomite	800
Pre-Cambrian			Quartzite, with various igneous rocks	

[1] 'Metallic Wealth of the United States,' 1854, p. 48.

Rocks older than the Cambrian do not outcrop at any point in the zinc and lead district, though they are known to underlie it. Since, however, the Cambrian and later beds are separated from the old crystallines by a pronounced and widespread unconformity, the underlying ancient rocks can have had no direct influence on the formation of the ores. The Cambrian is represented by about a thousand feet of water-bearing sandstone with minor beds of shale and dolomite. Ores occur in the Ordovician, principally in

FIG. 2. THE MOUNDS, THE UPLAND, AND THE RIVER TERRACES AS SEEN LOOKING SOUTH FROM GALENA, ILLINOIS.

the Galena and Platteville. In the lower lying, Prairie du Chien formation or 'Lower Magnesian' of the older reports, minor amounts of galena have been found both in Iowa and Wisconsin. Repeated attempts have failed to discover large deposits and in view of the situation, topographic and otherwise of such as have been found, the orebodies in the Lower Magnesian are believed to have been secondarily derived from those in the higher beds. Reasons for this belief are detailed elsewhere.[2] Between the Prairie du Chien and the Platteville is the St. Peters sandstone, one of the most unique and interesting formations in the Mississippi Valley. Made up of practically clean silica, usually poorly cemented, it extends in a great blanket under hundreds of square miles. It is everywhere

[2]Bain, H. F. U. S. Geol. Surv., Bull. 294, p. 119.

water-bearing and is a famous source of artesian wells. The universal presence of this sheet of artesian water sealed off from the ore-bearing beds above by clays at the base of the Platteville, effectually precludes entertaining any hypothesis of ore-bearing solutions rising from below.

The Platteville or 'Trenton' limestone lies next above the St. Peters. A generalized section is given below:

		Feet.
4.	Thin beds of limestone and shale	10 to 15
3.	Thin-bedded, brittle limestone, breaking with conchoidal fracture	25 to 30
2.	Buff to blue magnesian limestone, heavy bedded, in many places a dolomite	15 to 25
1.	Shale, blue, in some places sandy	1 to 5

Above the Platteville limestone, in the mining district, is a thick, massive dolomite, the 'Galena', which forms the main ore-bearing rock. It is made up of a granular, highly crystalline dolomite of dark-buff color. Owing to the predominance of solution over disintegration, it presents on weathered surfaces a very characteristic carious surface, marked by pits and rounded protuberances. In hand specimens it frequently shows small cavities of very irregular shape. These are often lined with dolomite crystals. When the rock weathers it breaks down into a coarse red sand, made up of individual crystals and crystalline particles of dolomite. Chert or flint is abundant in the median portion of the Galena, usually occurring through a thickness of about 100 ft. A general section of the formation is given below:

		Feet.
5.	Dolomite, earthy, thin bedded	30
4.	Dolomite, coarsely crystalline, massive to thick bedded	60
3.	Dolomite, thick to thin bedded, coarsely crystalline, chert-bearing	90
2.	Dolomite, thick bedded, coarsely crystalline; locally the lower portion is non-dolomitic and thin bedded	50
1.	Thin-bedded limestone with shaly partings which are highly fossiliferous, and in part, at least, carbonaceous—the 'oil rock' of the miners, usually with a well defined clay bed at the base	2 to 10

The basal member of the Galena, No. 1 of the above section, is well known throughout the zinc district. It receives its name from the large amount of organic material which it contains, often sufficient to cause it to burn when lighted with a match. In the mining district it is everywhere recognized as the 'oil rock'; and as there are usually several bands of shale interbedded with thin brittle limestone, the most important band is there discriminated as the 'main oil rock'. The individual bands of shale are generally thin and discontinuous, though the oil-rock horizon may be recognized throughout the district. It is a curious and significant fact that the oil rock is best developed in and about the mines, and that it is absent or poorly developed in the quarries and rock exposures between the mining districts. The oil rock is one of the most interesting materials found in the region, and its significance in relation to the ore deposits warrants the following rather full description. Chemically it consists of impure limestone impregnated with organic matter. Incomplete analyses show 'carbonaceous' matter to be present to amounts of 60.60%, 18.31%, and 15.76%. Tests by F. F. Grout show a content of 20.85% of volatile matter, with 7.95% of true carbonaceous material in thoroughly air-dried shale. Leaching the shale with ether gave a thick heavy oil, which is doubtless the most important element in the volatile matter and which contains an appreciable amount of sulphur. Rollin Chamberlin studied the volatile constituents of the rock with the following results:

"The oil rock is very porous and light, having a specific gravity of only 1.98 and yielding gas bubbles when placed in water. One volume of the rock gave 57.46 volumes of gas when heated to a red heat in a vacuum for two hours. A gas analysis of this material gave the following results:

	Per cent.
Hydrocarbon vapors	11.11
Heavy hydrocarbons	4.00
CH_4	35.98
H_2S	6.79
CO_2	18.12
CO	8.40
O	0.26
H_2	13.18
N_2	2.21
	100.05

"Under the term hydrocarbon vapors are here grouped various hydrocarbons which are liquid at ordinary temperature and which are soluble in alcohol. Benzine may be taken as a type. They contain more than 6 atoms of carbon per molecule. The heavy hydrocarbons are gases, such as ethylene, acetylene, and their analogues. In making this analysis the hydrocarbon vapors were first removed and determined, then the heavy hydrocarbons were absorbed, leaving only CH_4 of the strictly organic compounds to be determined. What percentage of this material exists in the rock in the true gaseous state is impossible to tell, though it is probably not a large proportion. Most of the gas, as the analysis indicates, came from the distillation and decomposition of various volatile hydrocarbons which give to the oil rock its name and precipitating properties. None of my analyses, with the exception of one of highly bituminous shale from Tennessee, have shown either hydrocarbon vapors or heavy hydrocarbons present. The excessive volume of the gas, 57, as against an average of 4 volumes per volume of rock, and the unusual amount of H_2S and CH_4 are the other notable features of the oil-rock gas. CH_4 rarely exceeds 5% in igneous or sedimentary rocks unless manufactured in the combustion tube from organic compounds present. In this case heavy brown tars were also evolved."

A microscopic examination of slides of the same material by David White led to the following conclusions:

"Thin sections of the light chocolate shale show it to contain minute, flattened, generally oval, and discoid translucent bodies of a brilliant lemon-yellow color that are highly refractive. These yellow bodies, usually thinly lenticular and irregularly rounded at the edges, but often nearly oval, are, in vertical section, seen to lie horizontally matted with other sediments and with crystals of later formation, precisely like the matting of forest leaves beneath the winter snow. While varying greatly in size, they accommodate themselves topographically when overlapping or surmounting the coarser rock material and seem to preserve their individuality even when apparently in contact. They are incredibly numerous, constituting over 90% of the rock mass in the richest layers. They are interpreted as the fossil remains of microscopic, unicellular, gelosic algae, apparently comparable to the living Protococcales. They appear to have been somewhat enriched in bitumen after the cessation of bacterial disintegration, which, in the buff shales, does not seem to have progressed sufficiently to form a noticeable fundamental jelly. The black oil shale differs from the light chocolate and buff rock chiefly by its deeper color, probably due to greater humification and bituminization of the gelosic bodies, and more particularly by the suspension of the latter in a dark-brown groundmass. This appears to consist of a fundamental jelly, largely filled with minute mineral matter and granulose fragmental débris or wreckage due to destructive bacterial action on the gelosic bodies, many of which, like the small fragments of larger associated algae, are greatly corroded. The oil shales owe their volatile hydrocarbon contents either directly or indirectly to the fossilized residues. The pelagic or floating algae fell in prolonged showers in quiet or protected areas where the water was presumably somewhat charged with tannic or humic solutions conducive to the early arrest of anaerobic bacterial decomposition. Possibly the bacterial action was arrested by its own products. The original deposits were doubtlesss several times as thick as those now remaining, since it is probable that the organic residue represents as little as one twelfth of the original volume. The Ordovician, like the Carboniferous gelosic algae, appear to have exercised an attractive or selective influence on bituminous compounds, particularly those of illuminant values, and to have consequently been permanently somewhat enriched. Portions of their hydrocarbon contents have doubtless been lost at various periods, and the great shrinkage of the shale which caused the collapse of the overlying limestone strata may have marked the first of these periods of hydrocarbon reduction. Presumably accelerated loss occurred at all times of rock folding in the region. Such an occasion might be favorable for the deeper zinc deposition."

Above the basal member the Galena is a very homogeneous dolomite, which through much of its thickness varies mainly in the presence or absence of flint. Analyses indicate that the rock is in the main a very pure dolomite. Outside of the mining district the formation is much less dolomitic. In fact, dolomitization extends from the top downward to a variable extent, reaching a maximum in the ore-bearing district where alteration has extended to the base of the formation. Individual zones of fossils have been traced horizontally from the limestone beds of the north into the dolomite farther south. It is believed that the alteration, while regional and secondary, followed close upon original deposition.

The Maquoketa formation is a thick shale with thin beds of dolomite in the upper portion. It occurs in the slopes of the mounds and escarpment (Fig. 2) and reaches out in fingers over the dissected peneplain over which the Galena and Platteville mainly outcrop. Above the shale and forming the caps of the mounds, is the Niagara, a massive cherty dolomite. The greater part of both formations within the limits of the mining district has been cut away by erosion. No mines have been found in either the Niagara or Maquoketa, though pieces of galena have been picked up occasionally in the areas which they cover.

The mines are distributed irregularly through the district in clusters, between which is barren ground where the country-rock is the same and conditions for concentration seem equally good. They occur within the limits of flat, shallow, irregular structural basins which are believed to be essentially depositional, slightly accentuated by deformation. These basins have been the subject of much careful study, and a number of them have been mapped by U. S. Grant and other members of the Geological and Natural History Survey of Wisconsin.[3] While it has proved impossible so far to detect any system in the distribution of these basins, four types may be discriminated: (1) broad, shallow, irregular basins; (2) flat monoclines; (3) sharply asymmetric anticlines; (4) canoe-shaped basins. In all of these the vertical element is slight. The first class includes depressions 20 to 30 ft. deep and 1½ to 2 miles wide. It is obvious that the beds here are practically horizontal, and it is difficult to conceive of their being laid down under the sea in any less level position. The flat monoclines show dips of 50 ft. in a half mile between areas of similar width of horizontal rocks. The asymmetric anticlines, such as the one at Meekers Grove, show dips of 90 ft. in a quarter of a mile. They represent, presumably, true deformation. The canoe-shaped basins are 20 to 60 ft. deep, from a half mile to a mile wide, and three to eight times as long. They are usually deeper at one end than the other, and represent true pitching troughs. The relations are such that there is ordinarily local artesian pressure within them, and when shafts or drill-holes penetrate below the 'glass rock' of the Platteville (No. 3 of section), a flow of water is common. Within basins the deposits are irregularily distributed, and the major trend of the individual deposit bears no constant relation to that of the basin. A characteristic canoe-shaped basin showing the distribution of mines and workings is illustrated in Fig. 3, based on surveys made by Grant and his assistants. The mine shafts are shown by conventional symbol. Old pits sunk for lead are indicated by small circles, old mine dumps by dots, and structural contours by black lines broken by figures giving the altitude, in feet above sea-level. The Mason mine, which is within this basin, is old and famous. Work began in 1833, and 20,000 tons of lead ore was yielded prior to 1853. The mine is still productive. Well marked pitches and flats occur in it.

Faulting is not characteristic of this district, and while minor faults occur the displacement is measurable in inches and is limited in extent. The beds are practically unfaulted. Joints, however, are well developed, both vertical and pitching points occurring widely. The best developed vertical points trend approximately,

[3] 'Report on the Lead and Zinc Deposits of Wisconsin, with an Atlas of Detailed Maps.' Wisconsin Geol. Nat. Hist. Surv., Bull. 14, 1906. 100 pages.

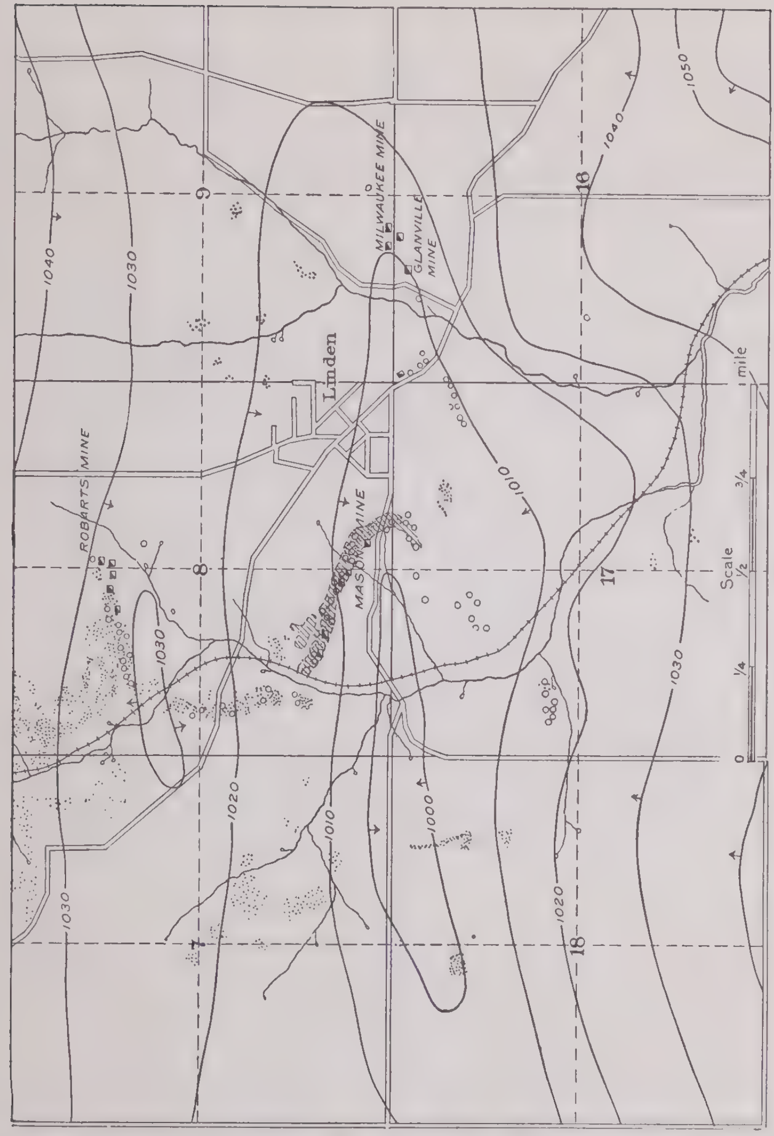


FIG. 3. CANOE-SHAPED BASIN NEAR LINDEN, WISCONSIN.
(After U. S. Grant, Wisconsin Geol. Nat. Hist. Survey.)

but rarely exactly, east and west. A less prominent set of joints runs at right angles to them, and these are locally called 'north-souths'. Quartering crevices also occur, and in individual areas may be more prominent than the main sets. Pitching crevices cross the beds at angles of 45° to 60° and strike at all angles. In the mines the east-west vertical crevices are most often open, and the pitching crevices may be traced completely around three-quarters of a circle.

ORES AND OREBODIES.

The ores of the region are simple in composition. They are made up largely of zincblende and subordinately of smithsonite, with soft lead, and iron sulphide. The complex sulphides and many of the gangue minerals found in the zinc-lead ores of the Rocky Mountain region are absent. Silver occurs with the lead to the amount of only an ounce to the ton approximately, copper is unimportant, antimony, arsenic, and fluorspar unknown, barite rare, and calcite the only common gangue mineral. Marcasite is abundant and pyrite rare. Silica and dolomite, while abundant in the region, rarely occur crystallized in the orebodies. There are four general forms of orebodies recognized in this region: (1) crevices and openings; (2) honeycomb or 'sprangle' runs; (3) pitches and flats; (4) disseminated ores. The ores are made up in large part of minerals which have crystallized in open spaces. To a subordinate degree they include metallic sulphides, metasomatically replacing dolomite, limestone, and shale. In the first three classes of orebodies metasomatic replacement has been strictly subordinate. In the disseminated ores it has been the most important process in their formation.

The ores first worked in this region occur largely in 'crevices', as they have long been locally called, for which J. D. Whitney[4] coined the term 'gash veins'. These he considered to be intermediate in character between segregated and true veins. They occupy pre-existing fissures, but are of limited extent, being usually restricted to a particular formation and not connected with any extensive movement of the rocky mass. As developed in this region, these veins occupy joint cracks. Usually, instead of a simple continuous fissure, there are a number of parallel fissures occupying *en échelon* positions. Collectively they are known as a 'range'. The crevices are developed along the vertical joint planes. The vertical joints, and hence the crevices, are best developed in the upper strata and within the first hundred feet of the surface. The joint planes are simple cracks through the rock. They are not planes of any appreciable faulting, and, though the vertical joints are very persistent, would not in themselves afford space for much ore. They have, however, been materially enlarged by the dissolving

[4] 'Metallic Wealth U. S.' 1854, p. 48.

action of underground waters. Locally this action has been fairly uniform along the plane, and space has been cut out in which a simple sheet of mineral from a quarter of an inch to as much as four inches in thickness has been deposited. This form of orebody seems to be especially characteristic of the crevices occupying north-south and quartering joints. Along the main crevices, which over most of the area are appoximately east-west in direction, solution has been more active, and irregular cavities and chambers have

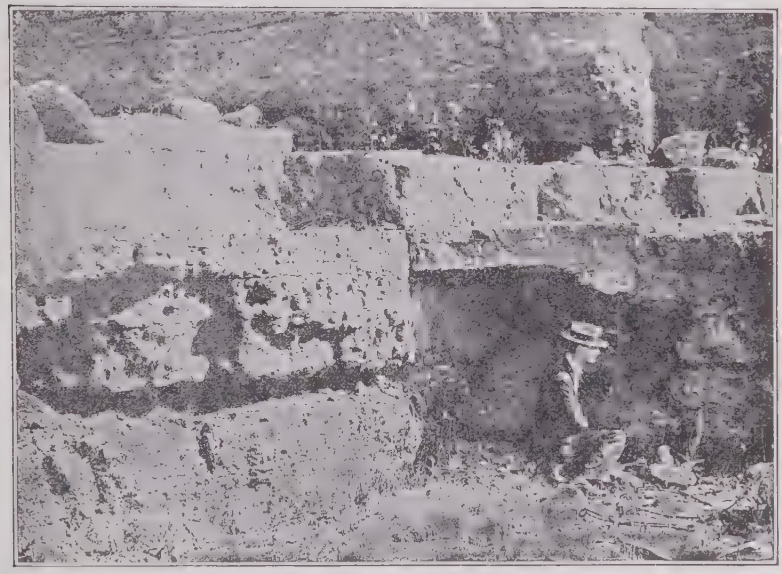


Fig. 4. Crevice and 'First Opening' in Weathered Galena Dolomite at Dubuque, Iowa. (From Iowa Geol. Survey).

been excavated. There is a tendency for these to form at certain stratigraphic horizons, which differ from camp to camp, but are fairly constant within the limits of small areas. At the intersection of these planes and the joint planes the crevice either widens out abruptly and an open space is formed, or the rock becomes soft and thoroughly disintegrated. In either case the term 'opening' is applied. The openings (Fig. 4) are usually from 1 to 4 ft. wide and from 4 to 6 ft. high. Occasionally the rock between two crevices has been cut by solution and broad chambers 25 to 30 ft. wide and 30 to 40 ft. high have been formed. The walls of the opening usually show firm dolomite, not especially disintegrated.

Frequently they exhibit a pitted surface very similar to that which the same dolomite takes on exposure to weathering agencies at the surface. The roof of the opening may either be a flat 'cap rock' through which the crevice can be traced only by a line of water seepage, or be irregular as a result of the presence of 'chimneys', which often extend as pipes from one opening to another. In many mines three distinct openings, one below another, are present. The ore occurs lining these openings or in loose fallen masses buried in residual sand. The term 'run' has been defined by W. P. Jenney[5] as "an irregular orebody found at the intersection of an ore horizon with a vertical fissure." The openings found in connection with the crevices might properly be spoken of, therefore, as runs: but since their essential feature is the open ground or a cavity only partly closed by fallen and usually oxidized rock, it seems desirable to retain the older local name.

Below water-level, where a considerable thickness of the Galena formation is present, there are typical runs. These correspond in position to the openings found above water-level and are believed to represent merely an earlier stage in the formation of the orebodies. At certain favorable horizons the ore penetrates the rock for a variable distance on either side of the crevice. In such cases the orebody consists of a porous dolomite with the interstices lined or partly filled with metallic sulphides. Locally the open spaces, which are half an inch to two inches in diameter, equal half the original bulk of the rock. Where the ore is very coarse and the fragments of rock are sharp angled, it is often spoken of as 'sprangle'. Where the material is less cavernous and there is less distinct evidence of brecciation, the term 'honeycomb' is more commonly used. In some cases the brecciation is evident, but in others it seems that the cavities are due mainly to solution. The two sorts of ore, corresponding roughly to 'honeycomb' and 'sprangle', pass into each other in the same deposits. In most cases it seems probable that originally the rock was brecciated or partly brecciated, allowing free access to circulating waters, and that these waters have enlarged the cavities by solution of the semi-brecciated or strained limestone. These honeycomb deposits occur in some places as small openings or enlargements of a crevice. They also make extensive deposits along vertical fissures and along flats. The open spaces in the honeycomb rock are ordinarily lined with a thin sheet of marcasite. On this, completely closing the smaller

[5]Trans. Amer. Inst. Min. Eng., Vol. 22, 1894, p. 189.

fractures and spaces and partly filling the larger ones, both galena and blende occur. In the Hazel Green mine typical honeycomb ore was observed. The gray dolomite showed small irregular cavities that were almost all lined with marcasite. This seemed to penetrate the dolomite slightly, becoming less and less abundant as distance from the cavity increases. The sheet of marcasite covering the surface of the cavity was 0.5 to 1 mm. thick. On it both galena and blende occurred. In the smaller fractures and cavities the galena when present seemed apt to occupy the entire space, and to show a uniform crystallographic orientation. Large spaces show the free crystallographic surfaces of the galena. Brown blende occurs in the same relations, but there is a notable tendency for each mineral to be segregated and to occupy different cavities or different portions of the same cavity rather than to be intergrown. This is not, however, an absolute rule. When water-level has sunk below the honeycomb deposits, they are partly or wholly oxidized, and zinc carbonate accordingly becomes the most important ore mineral. In such situations, no sharp line can be drawn between honeycomb runs and ordinary openings.

The most interesting and unique forms of orebodies in the district are the 'flats and pitches'. In these the ores follow in part the vertical joint planes, in part the bedding planes, and in part the dipping joint planes. The result is an orebody occupying a series of horizontal sheets, called 'flats', connected by a series of dipping sheets or 'pitches'. Many of these pitches are parallel to a main vertical crevice, and pitch outward from it on both sides. The ore spreads out along the bedding planes, both toward the main vertical crevice and away from it. It also descends from bedding plane to bedding plane by a number of parallel pitches. The deposition of the ore in the cavities formed by the combination of joints and bedding has usually been accompanied by minor metasomatic replacement of the country-rock, particularly that of the core between the two sets of pitches and the vertical crevice. T. C. Chamberlin was the first to recognize the peculiar character of these orebodies and to describe them adequately. While a number of the mines now working afford excellent examples of the pitches and flats and are described on later pages, Chamberlin's original description may be quoted to advantage:[6]

"The most curious and significant form of deposit is beyond question that of the flats and pitches. Among the numerous exam-

[6]Chamberlin, T. C. 'Geology of Wisconsin,' Vol. 4, 1882, pp. 469-470.

ples a few must suffice for special description. In some respects the Roberts mine, near Linden, though not the most important, furnishes the best initial example. The following typical section was made under the direction of John Poad and vertified by personal observation so far as the accessibility of the mine would permit. There crevices descend from above, one near the centre and one each on the north and south margins of the upper flat, the trend of the range being east and west. These crevices terminate in a fine flat opening about 40 ft. wide and 1 ft. in depth. On either side this descends by slopes and steps through the lower bed of the Galena limestone till the stratum known locally as the 'blue bed' is reached, at which point the divergent sheets are found to

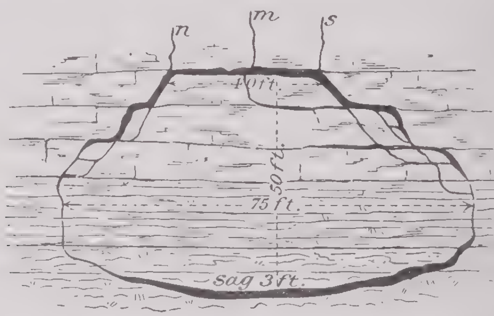


Fig. 5. Chamberlin's Cross-Section of 'Pitches and Flats.' Crevices *m*, *n*, *s*.

be 75 ft. apart. On the pitches the ore is from 2 to 8 in. thick. It usually follows one main crevice, but sometimes branches into minor seams, reuniting below. Through the 'blue bed' and what is here termed 'quarry rock' (not to be confounded with the 'Buff limestone' below, also known as 'quarry rock'), a narrowed seam descends nearly vertically. On reaching the 'brown rock' the crevice reverses its pitch, and on entering the 'glass rock' forms an extensive flat, 2 ft. in maximum thickness, having a central sag of 3 ft. Below this point the disposition seems to be toward impregnation of the rock rather than the formation of well defined veins. The depth from the upper to the lower flat is about 50 feet."

The cross-section given by Chamberlin and reproduced in Fig. 5, has been widely republished and has come to be considered typical. It has materially influenced the conception of the genesis of these peculiar orebodies and to some extent has served to direct exploration. While this section is entirely accurate, it is believed that certain misconceptions have grown out of neglect to remember that such cross-sections depict an orebody in only one plane. It is important to inquire more particularly regarding other planes, especially those at right angles to the one taken above. As presented in this cross-section and in those of the Marsden lode, Mills lode, and others, the presence of two outward-pitching orebodies parallel to the trend of the main crevice is emphasized. In Chamberlin's description of the Mills lode the fact is brought out that to the north there is a third equivalent pitch in the course of the old vertical crevice, or, to quote: "The form of this summit flat is not unlike that of a domestic flatiron, the sides gradually approaching each other and uniting in a point directed northward. On the east, west, and north—that is, on the sides and point—this flat breaks down into pitches that decline about 45°, that on the west being somewhat the steepest."[7] The accompanying figures leave no doubt as to the north pitch being exactly similar in all particulars to that on the east and west. The occurrence was long treated, however, as wholly exceptional, and the general notion of the parallelism of the vertical and pitching crevices became firmly fixed. U. S. Grant, in 1903, called attention to the presence in the Enterprise mine of pitches to the east and west as well as to the north and south.[8] In the sketch of the mine, Fig. 6, is shown at the southwest end of the upper workings a pitch that is in fact continuous around a half circle, uniting the north and the south pitches in one outward-dipping plane, similar to that in the Mills diggings described by Chamberlin. Such relations are so common that they are believed to represent normal conditions and to indicate that in ground plan the section of an orebody formed on pitches and flats is elliptical or circular rather than linear. The general relations of such an orebody to vertical and pitching crevices are illustrated in the map of the Empress mine at Benton, Wisconsin, made by E. T. Hancock, and shown in Fig. 7. A visitor to the region would be impressed mainly with the presence of those pitches which are parallel or approximately parallel to the main crevice, though this is because of secondary changes rather than because of their real predominance. Stresses which find relief along an east-west vertical crevice would be apt to emphasize a parallel pitching crevice, and underground waters flowing in a given direc-

[7]Chamberlin, T. C. 'Geology of Wisconsin,' Vol. 4, 1882, p. 476.

[8]Grant, U. S. 'Lead and Zinc Deposits of Wisconsin,' Bull. Wisconsin Geol. and Nat. Hist. Surv. No. 9, 1903, Fig. 6, p. 68.

tion, whether enlarging their channels or depositing ore, would be as likely to seek out and emphasize the pitching as the vertical crevices.

It is believed that the verticals, or crevices, and dipping joints.

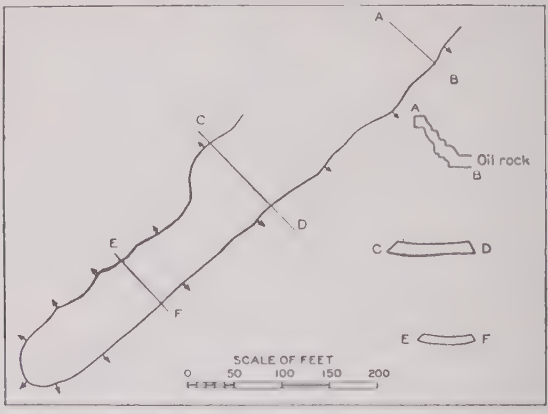


FIG. 6. SKETCH OF A PART OF THE WORKINGS OF THE ENTERPRIZE MINE, PLATTEVILLE, WIS., SHOWING GROUND-PLAN, CROSS-SECTION, AND 'PITCHES.'

or pitches, represent two different phenomena. The tendency of the pitches is to conform in strike to oblong or elliptical areas, with an outward dip in all directions. The flats and pitches are

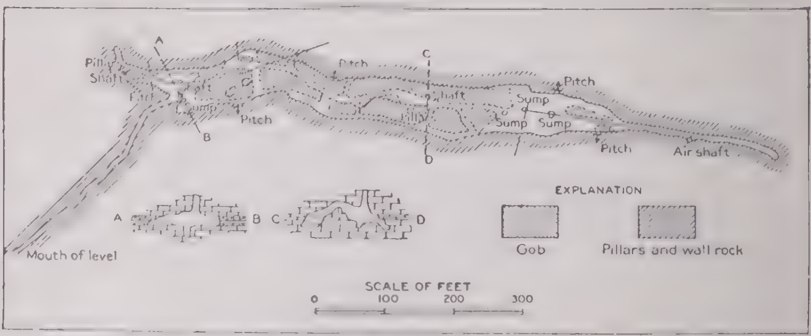


FIG. 7. GROUND-PLAN AND CROSS-SECTION OF EMPRESS MINE, BENTON, WIS.

best developed in the lower part of the Galena formation. They reach their maximum size and importance in the beds between the flint and the top of the Platteville limestone. They occur, however, as high as the top of the flint beds of the Galena and as low as the 'glass rock,' No. 3 of general section, p. 80 of the Platteville.

The characteristic ore of the flats and pitches is the zinc-sulphide ore. It is in them that blende and its associated minerals are most commonly found, though this may be due to the fact that they are rarely developed above water-level, as well as to their position low in the formation. Well developed pitches were found above water-level in the Stewart and Bartlett mine at Dubuque,[9] and yielded large quantities of galena ore. A similar body of galena was seen in a well developed pitch at Elizabeth in 1903. The ores found in the pitches and flats bear evidence of having been formed mainly in open spaces. Crustification is common and the various fracture planes and druses are lined or filled with the sulphides. In the great core of rock between the pitches there is a certain amount of disseminated ore, which is due to metasomatic replacement; but even here the rule seems to be that of deposition in open spaces.

In certain of the mines, particularly those in which the country-rock includes a considerable amount of clay or shale, both blende and galena occur in small scattered crystals, which do not apparently fill previously existing cavities. Such ore is known as disseminated ore, or frequently as 'strawberry jack' when the crystals are of blende and of about the size of strawberries. The ore forms flats, usually of slight vertical but considerable horizontal extent. These flats in ground plan form long irregular runs, and often show definite relations to vertical or pitching joints which come down through the roof. In other mines such relation is not apparent if present. Blende is more common in such orebodies than galena, and as compared with its occurrence in other forms of orebodies iron sulphide is rare. The crystals or crystalline masses of both blende and galena are usually sharp angled and idiomorphic. They vary from a sixteenth to three-fourths of an inch in diameter, and occur in certain mines in great abundance. This disseminated ore, as it occurs at the Enterprise mine, Platteville, is illustrated in Fig. 8. Such ore is found mainly in the lowermost beds of the Galena and the upper portion of the Platteville formation. It is most abundant in and near the oil-rock horizon. In the sag within the pitches, disseminated ore is common in the oil-rock. The disseminated ores represent metasomatic replacement of the rock by ore-bearing solutions. Their close association with the oil-rock horizon is believed to be due to its relative imperviousness and to its high content of organic matter suitable for the reduction of sul-

[9]Whitney, J. D. Iowa Geol. Surv. (Hall), Vol. 1, 1858, p. 450.

phate solutions. The disseminated ores lying below the horizon of the pitches and flats are yielding a rapidly increasing portion of the annual output. In a large way they are horizontal beds of rocks irregularly cracked and enriched by deposition of blende.

FIG. 8. DISSEMINATED GALENA METASOMATICALLY REPLACING OIL ROCK. ENTERPRIZE MINE, PLATTEVILLE, WISCONSIN.

marcasite, and galena. In general form and in the methods by which the ground is worked they show certain resemblances to the great lead deposits of southeastern Missouri.

ORIGIN OF THE PITCHES AND FLATS.

T. C. Chamberlin[10] was disposed to refer the formation of the pitching joints to deformation. They do not, however, seem to show that close relation to the folds which such a reference requires. There are evidently two different sorts of oblique joints present in the region. In the vicinity of Potosi there is a very small but very sharp little thrust fold, parallel to the crest of which are several well developed joint planes or crevices which pitch outward from the fold. These occupy the position, with reference to stresses, of the crevices developed by G. F. Becker in his experiments on schistosity and slaty cleavage,[11] and the explanation offered by him is entirely adequate for them. Similar crevices on a small scale have been noticed in the mines by C. K. Leith, and it is not improbable that they are present throughout the region. These crevices are different in several particulars from the ordinary pitches of the mines. The most striking and important difference is that the inclination of the crevice at Potosi is toward the basin, while it

[10]'Geology of Wisconsin,' Vol. 4, 1882, pp. 482-488.

[11]Becker, G. F. 'Experiments on Schistosity and Slaty Cleavage,' Bull. U. S. Geol. Surv. No. 241, 1904, Fig. 13.

is a universal rule that the pitches of the mines incline outward from the basin or sag in the mine. In the second place, these crevices parallel a thrust anticline, while in the mines the thrust phenomena are at least unrecognized, and the pitches strike in all directions. On the other hand, the relation of the pitching crevices to the minor sag, seen continually in the mines, is very definite. It is a rule having a few exceptions that the floor of the mine rises to the pitch and that on either side of the sag the crevices pitch outward. This would, it seems, warrant the reference of the pitches to the same agency that caused the sag, and they are, in fact, believed to be an expression of the settling of the rocks

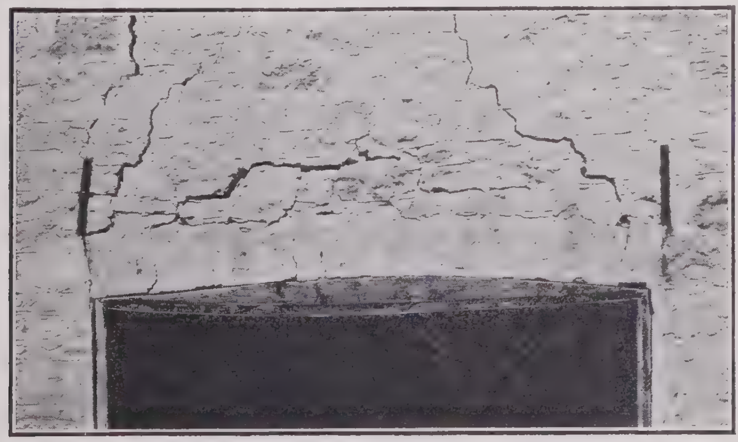


Fig. 9. Cracks in Stone Wall Due to Failure of Support.
(From photo by G. H. Cox.)

due to decrease in bulk of the oil rock. Anyone examining the ordinary cross-section of a typical sag and pitches will notice the resemblance of the fractures to those produced in a brick or stone wall where, for example, a window frame has failed to support its load (Fig. 9). The pitching fractures in this case arch upward over the settled portion, following in part the mortar joints between the brick in a manner strictly analogous to the flats and pitches in these mines. Fractures of the same sort may be found in the roof shales of coal mines where the load is not fully supported, and are, in fact, characteristic of such situations everywhere. Fractures formed after this manner should follow in strike the outline
4 of the settled mass. They should approach as they ascend and

should finally form an arch whose height is dependent upon the strength of the materials, the width of the area affected, and the amount of the settling. They do not require the formation of a corresponding set of fractures diverging upward, as would be true of those formed by vertical pressure affecting the whole thickness of the rocks.

The phenomenon seems to be clearly one of settling. That the suggested explanation is competent quantitatively may be indicated by a few calculations. Sediments as deposited are rarely dense. They contain much open space and are susceptible of considerable compression. This is truer of some sorts of sediments than others, but even in glacial till it has been shown that normal consolidation is enough to lead to the resurrection of rivers blotted out by a glacier and the re-excavation of valleys buried beneath a hundred feet or more of drift. Shales and coal settle even more in the process of consolidation, and the amount of this settling has been measured and its influence on succeeding formations studied in the case of coal in particular. It has been found that in many coal mines, where mountain-making forces have not complicated the conditions, the thicker coal lies in certain irregular channels or basins bordered by thinner coal. Toward the edge of the basin the coal rises and at the same time thins, and there is a fairly constant ratio between the amount of the rise and the decrease in thickness, ranging from 1:10 to 1:16. These facts are explained as due to deposition in initially irregular basins coupled with unequal settling due to the greater compressibility of coal than rock. This settling produces a basin in the overlying rocks if they be soft and yielding, as is shale, or causes fractures and faults if they be hard and unyielding, as are limestone and sandstone. These facts are significant in the present connection, since it is believed that bituminous shale undergoes the same changes as does coal, though to a less degree, the difference being due to the smaller amount of organic matter in the shale. The oil rock found in the basins of the zinc district contains now from one-third to one-half bituminous matter, and so may be assumed to have suffered compression in the process of consolidation, amounting to one-third to one-half that of coal. It may accordingly be assumed that 1 ft. of oil rock was originally equivalent to a bed of mud and decomposing organic matter 3 to 8 ft. thick.

It is difficult to make sure of the thickness of the oil rock itself, since the shale is often distributed in thin bands through a considerable amount of thin-bedded limestone. Bands of oil rock alone 12 to 18 in. thick are not uncommon, and a minimum thickness of 2 to 3 ft. of bituminous shale would probably not be too much to assume. This would be the equivalent of 16 to 24 ft. of original material, and its compression to its present thickness would be enough not only to lead to extensive fracturing in the beds above, but to accentuate in an important degree the original basis in which the deposition took place. It must be said, however, that such thickness of oil rock is not common, and an assumption of 1 to 2 ft., with corresponding settling of 2 to 14 ft., would be much more nearly correct. While this would still be enough to fracture the beds above and accentuate the basis, it would hardly account for any but the shallower ones.

It should be clearly understood that this is offered as an explanation of the minor sags in the mines and of the related pitches, and not of the large structural basins already discussed. The latter are believed to be depositional in origin, modified slightly by deformation. Slight original irregularities in the beds below the oil rock may have influenced the accumulation of the latter, but it was its consolidation and the settling thereby produced, which opened the peculiar cracks and pitching joints which, with the opened bedding planes, have become the 'pitches and flats'. These do not, to any considerable extent, as far as observation goes, extend below the shaly beds capable of such settling. Pitches and flats are not, so far as I am aware, found in any other important mining region. The descriptions of the lead mines of the North of England contain suggestions as to slightly similar forms. In Nevada, a zinc deposit shows relations to pitching joints suggestive of the type, and in some of the Joplin mines, underground solution and settlement have produced occasional pitches. Nowhere, however, aside from the Wisconsin district, are orebodies of this type common or normal.

GENESIS OF THE ORES.

A general discussion of the origin of the ores of this interesting district will not be here attempted. Such a discussion will be found by those interested in the report on the district already cited.[12] The ores are typically sedigenetic,[13] that is, formed by

[12] Bain, H. F. 'Zinc and Lead Deposits of the Upper Mississippi Valley,' U. S. Geol. Surv., Bull. 294, pp. 129-142, Washington, 1906.

[13] *Economic Geology*, Vol. I, pp. 351-339, 1906.

the processes which form sedimentary rocks, and concentrated as an incident to a sedimentary cycle. Their derivation through igneous agencies is excluded by (1) the known absence of any intrusive or extrusive igneous rocks of as late or later age than the rocks in which the ores occur; (2) by the presence under the area of unbroken sheets of artesian water in sedimentary beds,[14] precluding the rising of heated solutions from depths into these beds without dissipation; (3) the absence of faults or fissures reaching down into the lower beds, an absence confirmed by the presence, as stated, of underlying artesian waters, and (4) by the positive and sufficient evidence of the origin of the ores by other agencies. The metallic minerals now found in the ores were doubtless originally brought to the surface of the earth through igneous agencies. They were brought into this district by transportation incidental to deposition of sediments, from the pre-Cambrian rocks lying to the north. They were concentrated into their present condition by some phase or phases of the circulation of underground meteoric water. They represent the activities of descending waters if I may include under that term locally ascending currents. That the rocks of the district contain disseminated lead and zinc in sufficient quantity to allow the concentration of such orebodies as are present, has been shown both by inference and direct test. It has been customary to consider the ores as having been concentrated from the Galena limestone, and I have myself argued for a close correlation between the deposits and certain presumably originally richer portions of the Galena, related genetically to the irregularly distributed bodies of 'oil rock.' Certainly the distribution of 'oil rock,' pitches and flats, and orebodies shows much in common. And certainly any satisfactory explanation of the ores must account definitely for their localization, their limitation to particular areas in a region where generally favorable conditions are widespread. In the explanation which I have suggested this goes back finally to the paleogeography of the region, the relations of streams to sea coast. Years before, T. C. Chamberlin proposed a satisfactory hypothesis based on the distribution of ocean currents during the Ordovician. C. R. Van Hise has abandoned the attempt to determine original causes and explains the localization as due to certain controlling factors in the distribution, course, and flow of underground waters. Arthur Winslow's explanation of the Missouri deposits, if applied here, would make the whole a matter of residual concentration and would

[14] Norton, W. H. Iowa, Geol. Surv., Vol. VI.

necessitate finding explanation of localization essentially in local topographic features. G. H. Cox, who has studied the deposits recently for the Wisconsin and Illinois geological surveys, finds reason[15] to correlate their distribution with that of certain beds in the Maquoketa, similar in character to the 'oil rock' of the Galena. From this point their concentration would follow the general lines suggested by Winslow and Robertson, and Buckley and Buehler for the Missouri deposits. His conclusions are summarized as follows:

"It is held that the Maquoketa shale contains lead and zinc compounds as original minerals; that such a source is adequate; that this theory accounts for the lateral distribution of the ores; that it accounts for the vertical distribution of the ores without appealing to the secondary concentration; that it accounts for the occurrence of 'cog lead' and ranges; that the Maquoketa is as rich in organic matter as the oil-rock and of much greater thickness; that the concentration by downward moving solutions is by far the more simple explanation, using the movement of surface waters which we know is going on at all times."

RELATIONS TO ORE DEPOSITS IN GENERAL.

The actual processes of concentration may well have varied from place to place, and doubtless something of truth lies in each hypothesis. To students of ore deposits in general and to workers in other regions the most important fact is that there is here a large and important district in which lead and zinc occur and where the deposits bear no direct relation to igneous rocks. The discrimination of such deposits emphasizes the fact that an area in which no igneous rocks occur is not necessarily barren of minerals, but is only, so far as present observation goes, barren of the complex sulphides and precious-metal ores. In the Missippi Valley deposits of lead and zinc of the first rank have been formed through non-igneous agencies. Beds of copper ore, of less extent but still of commercial importance, have also been formed,[16] and it would seem that wherever large bodies of lead, zinc, or copper ores occur the possibility of concentration through action of non-igneous, as well as igneous agencies, should be kept in mind. Fortunately the criteria by which to discriminate at least those deposits independently produced by non-igneous agencies, are fairly certain. They

[15] Illinois State Geol. Surv., Bull. 16, pp. 36-39, 1910.

[16] Bain, H. F., and Ulrich, E. O. U. S. Geol. Surv., Bull. 267.

may be briefly summarized as below, neglecting placers, which may be considered as being derived forms from veins.

IGNEOGENETIC

Form. Frequently of fissure-vein type with irregular deposits usually showing some relations to fissures and faulting.

Composition. Characterized by the presence of scarce metals, particularly of gold and silver; extreme complexity and a wide variety of composition; arsenic and antimony compounds common.

Gangue. Wide variety of silicates present; fluorspar common.

SEDIGENETIC

Form. Frequently bedded or impregnations of beds; characteristically irregular and only most rarely similating fissure veins.

Composition. Characterized by the presence of the abundant metals and by bulk rather than variety of the minerals; simple composition; gold, silver, arsenic, and antimony, absent or unimportant.

Gangue. Extremely simple in composition; carbonates most common; silicates rare; barite in some districts; fluorspar entirely absent in most districts.

In the Mississippi Valley itself there is one district, that of western Kentucky and southern Illinois, where igneous agencies have co-operated in the formation of the ores, and the differences between the lead and zinc deposits of this area[17] and those of other parts of the valley are most instructive. Essentially they are fissure veins, consisting mainly of fluorspar but containing calcite, barite, quartz, argentiferous galena, blende, pyrite, chalcopyrite, and occasional crystals of stibnite. In the vicinity are certain lamprophyre dikes and sills, and the region is extensively faulted. That the dikes are of relatively recent age is shown by the fact that in Saline county, Illinois, they cut and coke coal beds of the Carboniferous. Incidentally a few crystals of blende were found in the coke at the contact. When attention is concentrated on the form, composition, and relations of these orebodies as contrasted with those in the Wisconsin district, it is seen that the evidence for the non-igneous origin of the latter is both positive and negative.

[17]Bain, H. F. 'Fluorspar Deposits of Southern Illinois,' U. S. Geol. Surv., Bull. 225, 1905, p. 61.

LEAD AND ZINC DEPOSITS OF THE OZARK REGION.

By E. R. Buckley.

The Ozark region is a dissected plateau, occupying a greater part of the southern half of Missouri and portions of Kansas, Oklahoma, and Arkansas. The St. Francois mountains are situated on the eastern flank of this uplift, the name being applied only to the hills of pre-Cambrian igneous rocks. A greater part of the Ozark region is occupied by formations belonging to the Cambrian and Ordovician. Flanking the region on all sides are formations belonging to either the Silurian, Devonian, Carboniferous, or Tertiary. Small isolated areas of Mississippian and Pennsylvanian strata are scattered, irregularly, over the Ozark plateau, which is almost surrounded by formations of these series. The Cambrian and Ordovician formations consist chiefly of magnesian limestone, sandstone, and chert. The Silurian consists chiefly of limestone, with a little shale; the Devonian is mainly limestone and shale; the Mississippian is chiefly limestone, cherty in places, with some shale and a little sandstone; the lower portion of the Pennsylvanian is chiefly shale and sandstone, while the upper portion is chiefly limestone and shale; and the Tertiary is mainly unconsolidated sand, gravel, and clay.

The different formations were not laid down in an unbroken succession, some being separated by well marked unconformities. The most important of these unconformities occur at the base of the Lamotte sandstone, which rests upon the pre-Cambrian igneous rocks; at the base of the Mississippian, which rests upon several of the older formations, including the Silurian, Ordovician, and Cambrian; and at the base of the Pennsylvanian, which rests upon the Mississippian and older formations of the Paleozoic.

As a result of uplift, the beds have been, in some places, slightly folded and faulted, and everywhere conspicuously jointed. The faulting in this region, as far as known, occurs chiefly in the eastern part of the Ozark region, in close proximity to the St. Francois mountains and in northern Arkansas.[1] There is some faulting in other parts of the region, but it is not conspicuous, and it is seldom associated with the more important deposits of lead and zinc ore.

The Ozark region is characterized by two quite distinct types of deposits of lead and zinc ore of great commercial importance. One of these occurs in the oldest Cambrian dolomite of southeastern Missouri; the other occurs in the Carboniferous of southwestern Missouri, southeastern Kansas, and northeastern Oklahoma. The former is known as the 'disseminated lead' type and the latter as the 'Joplin lead and zinc' type. In the formations lying between those in which occur the ores of these two districts, are many smaller or less well developed bodies of lead and zinc ore in the so-called Central Missouri and Missouri-Arkansas districts. In the Central Missouri district are well defined veins of lead and zinc ore, which constitute a third type of subordinate commercial importance.

THE SOUTHEASTERN MISSOURI DISTRICT.

The 'disseminated' lead deposits of the Southeastern Missouri district, according to our present knowledge, lie mainly within St. Francois, Washington, and Madison counties. The deposits in St. Francois county have yielded by far the greatest quantity of lead; in the aggregate something over 1,500,000 tons of galena since their discovery in 1864. This does not take into account the lead, obtained from the shallow deposits occurring above the disseminated lead, which was mined as early as 1700 and largely exhausted prior to the discovery of the disseminated deposits. This district is now the greatest producer of lead in the United States. The disseminated lead ore occurs mainly within a single formation known as the Bonneterre dolomite, although it is also found within the underlying Lamotte sandstone near its contact with the Bonneterre. Also, where the Lamotte sandstone is absent, the galena sometimes occurs in the few feet of conglomerate which separates the Bonneterre formation from the pre-Cambrian granite.

The surface of this district is rough and hilly, there being a difference in elevation of about 1100 ft. between the highest point, 1800 ft. A. T., and the lowest point, about 700 ft. A. T. The highest hills are mainly pre-Cambrian igneous rock; a result of erosion,

[1]My knowledge of the faulting in the Arkansas region is chiefly from published reports. Although I have observed some faulting, I have never spent enough time in this district to determine the extent of the faults observed or to verify the observations of others.

mainly prior to Middle Cambrian, and subsequent faulting. Tributaries of the Big and the St. Francois rivers drain the entire area. There are many springs and occasional caves and sink-holes.

The geologic succession in this district is simple, there being but a complex of igneous rocks overlain by a series of practically undisturbed sedimentaries. The igneous rocks are of pre-Cambrian age[2], probably belonging to the great granitoid series of the Archean, as recognized by the United States and Canadian geologists. They consist mainly of granite and porphyrytic rhyolite, although at intervals throughout the district diabase dikes occur, intrusive in the granite and rhyolite. Narrow veins of galena and some sphalerite occur within this pre-Cambrian complex and analyses seem to indicate that the igneous rocks, when fresh, contain minute quantities of both lead and zinc.

The pre-Cambrian is separated from the overlying sedimentaries by an unconformity corresponding to at least a part of the Algonkian and all of the Lower Cambrian. The Lamotte sandstone is the oldest of the sedimentary formations of this district. It has a known maximum thickness of about 250 ft., thinning out along the flanks of the pre-Cambrian hills to a feather edge. It is usually conglomeratic at the base and sometimes slightly conglomeratic at the top. The Bonneterre formation overlies the Lamotte conformably. There is usually a series of transitional beds consisting of arenaceous dolomite and shale. In the lower part of the formation there is more or less black, brownish, or greenish-blue shale inter-bedded with the dolomite. Some of the dolomite in the lower part of the formation, as well as some of the shale, has a greenish color due to the presence of small granules of chlorite. The formation has an average of normal thickness of about 370 ft. The maximum thickness is about 440 ft. Galena has been mined throughout the entire thickness of this formation, the near surface deposits being in the shape of aggregates of cubes either loosely embedded in the residual clay or in the crevices and caves. The deeper deposits are of the 'disseminated' type.

The Bonneterre formation is overlain by beds of a maximum thickness of 200 ft. consisting of shale, thinly bedded limestone and dolomite, and limestone conglomerate, the whole known as the Davis formation. This is overlain conformably by thick-bedded

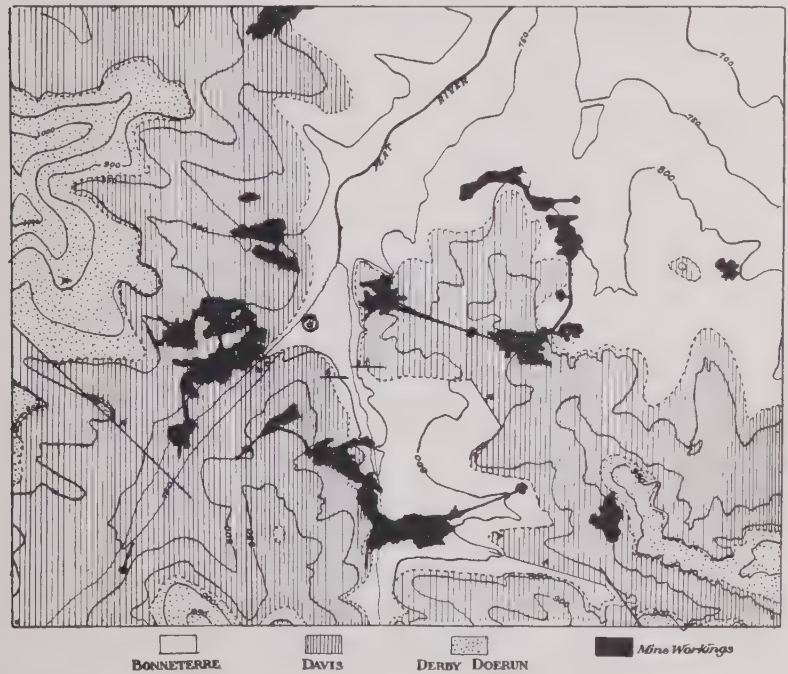
[2]In two places in Ste. Genevieve county I have observed basic igneous rocks, containing visible quantities of galena and sphalerite, which appear to be intrusive within the lower part of the Bonneterre formation.

dolomite, aggregating 40 ft. in thickness, known as the Derby formation. The Derby is conformably overlain by a thickness of 60 to 100 ft. of argillaceous dolomite, which comprises the Doerun formation. The Doerun is overlain by about 300 ft. of dolomite, containing abundant quartz druses, known as the Potosi. There are many shallow lead mines in this latter formation, the galena occurring associated with sphalerite, smithsonite, barite, and pyrite, in crevices and other openings partly filled with a sticky red clay. Overlying the Potosi there are remnants of younger formations belonging to the Cambrian, while over the hillsides are strewn beds of gravel belonging to the Tertiary. It is thought that this region was once covered by a part of the Pennsylvanian, a part of the Misssissippian, and probably with other formations, since eroded.

Structures.—As a whole, the different orebodies of the district lie in pitching troughs, as shown by the accompanying sections of the Flat River area. The central part of this area shows the Bonneterre formation, while on either side and at the upper end there is a broken rim of Lamotte sandstone, beyond which occur the pre-Cambrian igneous rocks. The igneous rocks are brecciated in places and exhibit joint and fault planes. The rhyolite also shows flowage structures. In some parts of the district the rocks have suffered very little decomposition, practically unaltered rocks reaching the surface. In other places weathering has extended to a depth of 10 or 15 ft. There is little evidence of intense deformation such as is usual in mountain masses. The sedimentary series has in some places retained its original, approximately horizontal position, but usually there is a gentle dip in one direction or another. Occasionally the beds dip as much as 45° from the horizontal, but this is exceptional.

The faults present are of the branching type and occur in zones, there being as a rule several nearly parallel planes along which movement has taken place. A great majority of the faults show at the surface and extend downward through the Bonneterre and perhaps into the pre-Cambrian, but there are others that only show near the base of the Bonneterre, dying out before they reach the surface. Along the fault zones the rock is usually badly decomposed, often through the entire thickness of the Bonneterre. The faults take a zigzag course across the country, frequently branching. There are two well developed systems of faulting having general northeast and southeast strikes, respectively. These faults are of the so-called 'normal' type, and usually have throws of less than

100 ft. There is one fault zone in which the displacement amounts to about 700 ft.; a second in which the displacement amounts to about 600 ft.; a third in which the displacement is about 400 ft.; and a fourth in which the displacement is about 120 to 150 ft. The first three are approximately parallel, while the fourth is practically at right angles. These faults are outside of the orebodies thus far developed, and in two instances, at least, they appear to limit the



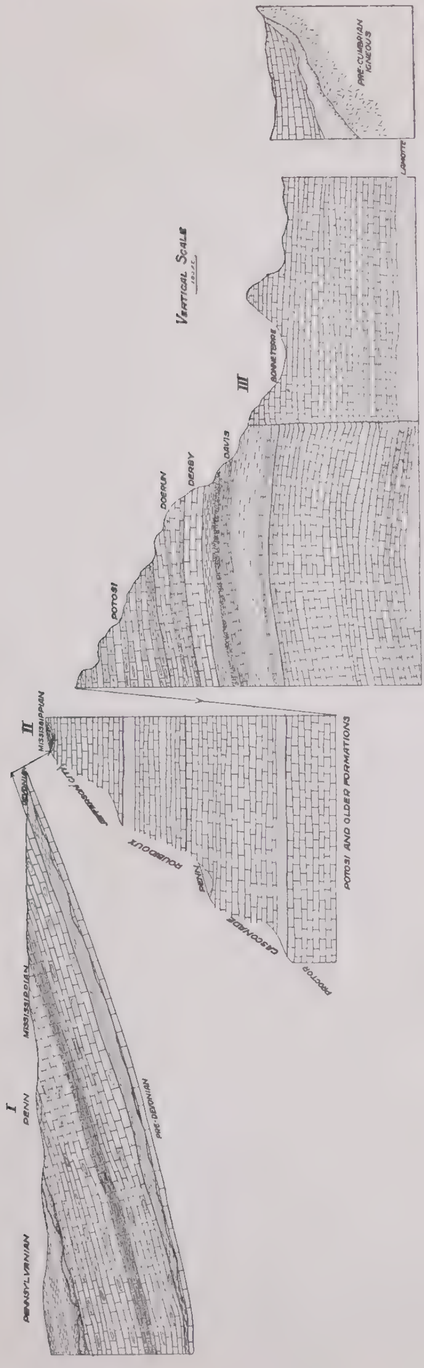
Topography and Geology of an Area, 2¾ by 2¼ Miles, at Flat River, Missouri. Shows Relation of Mine Workings to Topography and Geology.

area of profitable prospecting within the Bonneterre formation. There are many lesser faults within the orebodies. Movement along the bedding planes and laterally along joint planes has also been observed in different places.

The Ore-Horizons.—In this district the galena occurs principally in the Potosi and Bonneterre formations, although it is known to occur also in the Lamotte sandstone and in the pre-Cambrian granite and diabase. In the granite it occurs in veins which, as far as discovered, have been too small for profitable exploitation. In the diabase the galena occurs with sphalerite disseminated through the rock, but has never been mined successfully.

In the Potosi the ore is mainly in the upper 100 to 150 ft., which is characterized by channels and other openings. The openings, in which the ore chiefly occurs, are either along vertical joint planes or along horizontal bedding planes. The galena occurs in masses or aggregates of cubes in vertical channels, in horizontal pipe veins and in the residual deposits of clay and flint covering the surface. Associated with the galena occur barite, iron pyrite (usually marcasite), limonite (pseudomorphs after marcasite), sphalerite, smithsonite, cerussite, and calcite. The corners of the galena crystals are usually rounded and the surfaces corroded, both of which are evidences of leaching. The orebodies in the Potosi are extremely irregular and, as far as can be made out, the areas in which the ores occur are distributed without any well defined system. The runs in the mines usually follow channels or similar openings along what were formerly joint planes, spreading out laterally along bedding planes where openings have been formed through solution. The galena is seldom a replacement product, having evidently crystallized from dilute solutions of lead salts. In this it differs materially from the disseminated lead ores of the Bonneterre formation.

There are really two types of ore deposits in the Bonneterre formation. The galena in the upper part of the formation resembles, in the manner of its occurrence, the ores of the Potosi formation just described. It occurs in masses or in aggregates of crystals embedded in the mantle of residual clay at the surface and in crevices, caves, or caverns, either loosely embedded in a sticky, reddish brown clay or attached to the roof and sides of the openings. The galena crystals usually have their corners rounded and their surfaces corroded, as a result of leaching. This type of ore does not predominate below a depth of about 50 ft., although it actually occurs with the disseminated deposits at greater depths. Although the crevices in which the galena occurs have been found to usually pinch out at a depth of less than 50 ft., some of the veins extend nearly to the underlying sandstone. As in the case of the Potosi formation, this galena must have been the result of precipitation from dilute lead solutions. It is significant that these shallow deposits of galena rarely occur in the Bonneterre where that formation is overlain with any part of the Davis shale. The Davis shale has evidently been instrumental in directing the circulation of the



GENERALIZED SECTION ILLUSTRATING POSITION AND RELATIONS OF ORE-BEARING STRATA. I. SECTION OF ROCKS ASSOCIATED WITH JOPLIN DEPOSITS. II. ROCKS OF CENTRAL DISTRICT. III. ROCKS OF SOUTHEASTERN DISTRICT.

ground-water, and it may also have supplied elements required for the precipitation of the galena.

The Disseminated Ore.—The second type of ore deposit in the Bonneterre is the 'disseminated', which has supplied the greater part of the lead mined in this district for the past 45 years. The disseminated galena occurs at different depths from the top to the bottom of the Bonneterre formation, although a majority of the rich orebodies occur at or below a depth of 200 ft. in the Flat River and Bonne Terre areas. In nearly every instance these are closely associated with the shallow deposits in the upper part of the formation. Orebodies of commercial importance have not been discovered in any part of the district which is underlain with formations younger than the Davis shale, although occasionally tongues of the orebodies project laterally into the Bonneterre underlying the Derby and Doerun. In this they nearly correspond with the shallow deposits in the upper part of the formation. The accompanying illustration shows the approximate limits of one of the orebodies in the Flat River area with respect to the formations occurring at the surface. In this it will be seen that the contact of the Davis shale and the Derby limestone marks the approximate limit of the orebodies as shown by detailed drilling over the area represented in the drawing.

The galena in the disseminated lead orebodies does not occur exclusively in the disseminated form, although this is the type that especially characterizes the deposits. The full list of modes of occurrence includes: (1) disseminated through dolomite, shale and chloritic rock; (2) in horizontal sheets along bedding planes; (3) filling or lining the walls of joints; (4) in cavities, vugs, and similar openings, sometimes embedded in soft blue clay or mixed with calcite and pyrite; (5) in shale along fault planes; (6) in cubes and aggregates of cubes in red clay, filling channels and large openings along fault zones; (7) as cerussite in decomposed dolomite. Several of these types of deposits are shown in the accompanying illustrations. It is thought that not to exceed 75% of the ore mined should be classed as disseminated. The remainder of the galena occurs in the form of sheets, filling openings along bedding planes, lining cavities in the rock, etc., as indicated above. The ore which is commonly spoken of as disseminated contains both galena crystallized in small vugs and that which is a metasomatic replacement of the dolomite. As a rule the bodies of disseminated ore in the upper part of the formation are small and irregular as compared with those in the lower levels. The deeper orebodies have the greatest lateral extent and are the more uniform in the quantity of galena which they carry. In the upper levels of the mines there is abundant evidence of leaching shown by partly removed crystals of galena. Leaching has also occurred, though to a much less extent, in the lower workings. The bunchy character of the orebodies in the upper levels is thought to be partly due to this leaching process, although it is also, in part, attributable to the originally irregular distribution of the galena which was controlled by the distribution of the reducing constituents.

From observations in the mines, it is clear that there is a surface and a deep ground-water circulation and that these are connected through channels and fault zones extending from the surface to the Lamotte sandstone underlying the Bonneterre dolomite. The water of both the upper and lower circulations carries lead in solution, according to analyses made in the laboratory of the Missouri Bureau of Geology and Mines. The mine waters contain, besides lead, iron, manganese, calcium, sodium, potassium, silicon, and aluminum. As pointed out elsewhere, there is, in the Bonneterre formation, a series of fractures extending downward from the upper surface and another series extending upward from the bottom of the formation. Some of these fractures or zones of fracture continue through the entire thickness of the formation, although many of them are relatively short and are confined to either the upper or lower portion. The rock walls bounding many of the joints and faults have been leached and weathered. In fact, the orebodies usually die out as these so-called channels are approached, owing to the removal of the galena by oxidizing solutions which have circulated abundantly through them. Thus it appears that the Bonneterre formation is provided with channels for the free communication of the circulating waters between the surface and the Lamotte sandstone. Some portions of the formation are well supplied with both upward and downward trending fissures, along which the surface-waters and the waters from the Lamotte sandstone may find entrance to all parts of the formation. Communication between neighboring fissures is provided by the bedding planes along which the water may readily find its way. In some places the rock along these horizontal bedding planes has been leached to such an extent as to carry the oxidizing solutions beyond the vertical fissures without coming in contact with reducing conditions which otherwise would cause the lead to be deposited. Connection between the adjacent bedding planes is also supplied by short joints which may be confined to one or several beds.

The disseminated galena occurs most abundantly in the shale and dolomite, which are carbonaceous or bituminous. The dark-brownish dolomite and the black shale provide a reducing medium in which the lead salts are precipitated. The lead solutions supplied to this reducing medium come both from the dolomite above and from the sandstone beneath. However, the water in the sandstone comes originally from the surface, being introduced along channels, the walls of which are completely oxidized, or through the sandstone which outcrops between the Bonneterre dolomite and the bordering pre-Cambrian igneous rocks, a non-reducing medium. On the other hand the metallic salts, contained in the water rising from the Lamotte sandstone, are not all deposited at or near the base of the Bonneterre formation, since it may rise in some places for a considerable distance along channels which are oxidized above the Bonneterre-Lamotte contact.

The conditions are about as follows: A zone of oxidation near the surface containing galena which is being abstracted by the ground-water; a porous formation, the Lamotte sandstone, serving as an enormous storage reservoir of water containing lead in solution; and, between the two, a carbonaceous or bituminous and chloritic dolomite and shale (the Bonneterre formation) of a reducing nature, in which the galena has been and is being deposited. The oxidizing zone at the surface connects with the sandstone horizon by means of channels along which the rocks have been and are being oxidized, permitting the direct transference of oxidizing solutions, carrying lead in solution. The water held by the sandstone is also introduced along the sandstone outcrops and undoubtedly is derived, in part, from the circulation in the upper part of the granite and rhyolite which outcrop along the margin of the sandstone. The dolomite along these channels, which is now oxidized, was at one time unaltered and probably in places reducing in nature. This is evidenced by the galena which occurs in places adjacent to these channels. At such time any oxidizing solutions, carrying lead, which penetrated the lower horizon of the Bonneterre formation must have been brought in from other areas, chiefly through the rock outcropping near the areas of igneous rocks. The galena in the crevices may have been introduced by ground-water from the surface, or, in part, from water rising from the Lamotte sandstone. It is thought, however, in the absence of oxidized channels through the Bonneterre connecting the surface with the Lamotte sandstone, that the water issuing from the sand would contain very much less lead than at present, and that the orebodies are mainly subsequent to the establishment of zones of communication along oxidized channels.

The Bonneterre formation, which provides abundant conditions for reduction of metallic salts, is a great reducing medium, which, under the physical conditions described above, has become soaked in dilute lead solutions, the lead of which has been derived almost entirely from the successive decomposition of dolomite, limestone, shale, granite, and rhyolite of the tributary catchment area. The disseminated orebodies are in part the result of the abstraction of lead from waters circulating along channels and bedding planes in their journey from the surface to the sand; and in part from solutions, under hydrostatic pressure, which rise along channels extending upward into the dolomite, from the underlying sandstone. Oxidation of the lower part of the Bonneterre formation in the region of the orebodies has not progressed far, and the orebodies at the lower levels have not suffered greatly in consequence thereof. Further, the lower portion of the Bonneterre presents, through the carbonaceous or bituminous character of the dolomite and shale, a more persistent horizon for reduction. These facts account for the better development of the orebodies near the base of the formation. Furthermore, the fracturing of the dolomite is more general and better developed near the base of the formation than it is in the upper levels, permitting a more uniform saturation of this part of the formation with the lead-bearing solutions from the sand. There may have been some very finely disseminated galena deposited in the bituminous horizons when the sediments were being deposited in the ocean. If this were the case, chemical affinity would have been active in abstracting, at such places within the formation, the galena carried by the ground-water.

It is difficult to indicate the time when the solutions carrying lead were first introduced. There may have been several periods of concentration at the same horizons in this formation, scattered along from the Cambrian to the present time. It is believed, however, that the major part of the disseminated ore is of comparatively recent age, younger than Pennsylvanian. The investigations that have been made seem to show that the Davis shale, overlying the Bonneterre formation, must have been, in part at least, removed prior to the introduction of the lead-bearing solutions from which the disseminated lead ores were derived. The impervious shale would not only have prevented a free circulation of the oxidizing solutions from the lead-bearing Potosi dolomite, but would also have interfered with the upward circulation from the Lamotte sandstone. Erosion may have cut through the Davis shale prior to the Pennsylvanian, but of this there is no good evidence. If this were the case, the disseminated orebodies probably began forming during that period. Since Pennsylvanian time there have been several periods of elevation and subsidence during which the horizons which now appear at the surface were alternately within the zone of weathering and within the zone of cementation.

The ores of the district, whether they be in the Potosi or in the Bonneterre—massive or disseminated—belong to the 'descensional'[3] class. The orebodies are the result of lateral secretion only in so far as portions of the dolomite may have come within the zone of weathering and thereby have had the galena abstracted and removed to other parts of the same formation.

The investigations so far carried on fail to produce evidence that might indicate that the sedimentary rocks of this area were ever saturated with hot solutions or impregnated with gaseous emanations rising from known or unknown depths, from known or unknown sources. Pneumatolitic action does not deserve serious consideration in a study of the ore deposits of this area, since there is no evidence of igneous activity subsequent to the Algonkian. There is nowhere evidence that hot springs were active during any period of the sedimentary history of the area. Neither have we evidence that these formations were buried, at any time, deep enough to materially increase the temperature of the ground-water. There is, likewise, no evidence that the galena, as now found, was deposited, mechanically or chemically, in the dolomite at the time the dolomite was laid down, except in minute quantities, as has been referred to above.

It is believed that the original source of the minerals was the igneous rocks. As a result of the decomposition and disintegration of these rocks the lead was probably in part taken into solution and

[3]Descensional ores are those that have been transferred from higher to lower altitudes. During their transfer they may be carried by downward, upward, and lateral moving waters, but the sum total of this movement must result in bringing the ores to a lower plane with respect to the sea-level. The transference may be from older to younger rocks or vice versa.—'The Geology of the Disseminated Lead Deposits of St. Francois and Washington Counties, Missouri,' Missouri Bureau of Geology and Mines, Vol. IX, Pt. 1, p. 208, 1908.

carried downward into the joints and other openings where it was concentrated for the first time. The lead-bearing solutions which did not become a part of the underground circulation, probably issued again in the form of springs, and mingling with the water which flowed directly off from the surface, were removed by the surface streams to the ocean. These processes of solution, transportation, and concentration were probably repeated many times between the pre-Cambrian and the present; for which reason, in considering the origin of the ores of this district, three important factors should be kept in mind: (1) that through the processes of disintegration and decomposition, the minerals at or near the surface of the earth are being in part taken into solution; (2) that all materials within the zone of weathering are being transferred, either in suspension or in solution, from one place to another; (3) that the removal of certain minerals results in the concentration of those remaining. Minerals, such as galena, are probably removed chiefly in solution either by the surface or underground circulation, while barite, on the other hand, is removed chiefly in suspension. These processes, which are conceived to have been in operation repeatedly in the past, are operating today; and with the disintegration of the dolomites lead is being added to the surface and underground circulations. The leaching of the minerals near the surface, their transference to the ocean or migration downward, and their redisposition, either at greater depths or with the sediments of the ocean, have been accomplished in the same manner and through the same agencies through all ages. The entire process has been clearly one of concentration. Just as water underground or upon the surface is collected through myriads of channels into streams, after having been sprinkled over the surface, so have the mineral salts been gradually concentrated as they moved from broad catchment areas to restricted portions of the continental plateau or downward by a gradually diminishing number of crevices into the crust of the earth.

THE JOPLIN DISTRICT.

This district, according to present knowledge, comprises about 3000 square miles in southwestern Missouri, about 40 in southeastern Kansas, and about 40 in northeastern Oklahoma, the different camps being distributed throughout this area. Over 80% of the production has been obtained from an area of about 100 square miles, all of which lies within 14 miles of Joplin, from which city the district derives its name. Since the discovery of the ore deposits in this district in 1850, the mines have yielded approximately 1,100,000 tons of lead concentrate and approximately 4,700,000 tons of zinc concentrate. Nearly 65% of the lead was mined prior to 1893, while about 98% of the zinc has been mined since 1880. At the present time the district produces about one ton of lead concentrate to seventeen of zinc.

The lead and zinc ores of this district occur chiefly in the formation known as the Burlington or Boone. They are also found in the overlying Chester and Cherokee; and lately they have been reported as occurring in the underlying Kinderhook.

The surface of the district is comparatively level, most of it being a rolling prairie. Outside of the Springfield area the differences in elevation between the highest and lowest points are seldom more than 500 ft. The elevation at Baxter Springs is about 780 ft. A. T., while the more elevated tracts in the vicinity of Granby are 1200 ft. A. T. The hills and valleys are mainly the result of stream erosion. The chief river systems are the Osage, the Neosho, and the James. The first flows into the Missouri river, and the latter two are branches of the Arkansas and White rivers, which flow into the Mississippi. The drainage of this area is in some measure superimposed upon the drainage of the pre-Pennsylvanian erosion interval. It is not altogether controlled by this ancient drainage, having been modified by the structures and differential hardness of the rocks. The direction and depth of many of the valleys and stream channels have been greatly influenced by the solution of the limestone by underground waters. The hard masses of chert conglomerate at the base of the Pennsylvanian have had a tendency to deflect the courses of the streams, while the soft Pennsylvanian shale has invited the streams to meander in the pre-Pennsylvanian channels. On the other hand, the warping of the surface has had a tendency to divert the streams from the ancient river courses, the tilting of the strata being in a different direction from that of the flow of the pre-Pennsylvanian streams. There are occasional springs and numerous sink-holes and caves throughout the district.

The geological succession in this district, as in the disseminated lead district, is simple, consisting mainly of practically undisturbed sedimentaries of Carboniferous age. The oldest rocks are in the neighborhood of Springfield, in the eastern part of the district. In this area the dolomites and sandstones of the Upper Cambrian are exposed.

The Cambrian is separated from the overlying Ordovician in this district by an unconformity. The only representative of the Ordovician is the St. Peters sandstone, which in turn is overlain with a shale formation, the Hamilton, which has been considered by E. M. Shepard as belonging to the Devonian.[4] The hiatus between the Ordovician and the Devonian evidently represents a part of Ordovician and all of Silurian times. The Kinderhook formations, belonging to the Mississippian, overlie unconformably the Hamilton and are represented by the Chouteau limestone, the Hannibal shale, and the Louisiana limestone. The Chouteau is overlain conformably with the Burlington and the Keokuk, which together are also known as the Boone. The Burlington is the principal ore-bearing horizon of the district. Above it occur beds of sandstone, coal, and shale, which have been separated into two series, the lower belonging to the Chester formation of the Mississippian, and the upper to the Cherokee division of the Pennsylvanian. The coal beds occur exclusively in the upper series. The Chester[5] is separated from the Burlington below and the Cherokee above by well-marked unconformities. The Burlington formation, in which the ore deposits chiefly occur, consists of from 250 to 350 ft. of limestone, cherty limestone, and chert. The upper part of the formation consists of about 100 ft. of practically non-cherty, thoroughly crystalline limestone, known as the Carthage. Beneath this is a massive bed of öolitic limestone from 2 to 8 ft. in thickness, known as the Short Creek öolite; a crystalline limestone horizon with interbedded layers of chert and containing nodules of chert, about 100 ft. in thickness, unnamed; a chert horizon from 10 to 60 ft. in thickness, known as the Grand Falls chert; and a lower cherty limestone, having a thickness of from 25 to 150 ft., which may be in part the Kinderhook.

The erosion intervals following and prior to the Chester were the most important epochs in the geological history of the region. During them the formations were deeply trenched by streams flowing over the surface and by the circulation of the ground-water which dissolved the limestone, producing caves and sink-holes. During these periods the limestone became more thoroughly crystalline; the original chert nodules were enlarged by the replacement of limestone by silica; and the limestone, itself, was in places silicified.

[4]See report on Green county, Vol. XII, Missouri Bureau of Geology and Mines, 1898.

[5]C. E. Siebenthal named the local representative member of the Chester, the Carterville.—Joplin District Folio, U. S. Geol Surv., pp. 6, 1907.

There is no evidence that either lead or zinc was deposited during these periods. The Mississippian limestone was probably subjected to a longer period of erosion, prior to the Pennsylvanian, than it has been since. From the evidence at hand it is difficult to determine which of the erosion intervals referred to above chiefly is responsible for the modification of the Mississippian. In a discussion of the ore deposits they are usually referred to as one, the belief being that the interval between the Chester and the Pennsylvanian was of much greater duration.

The close of this erosion interval left the land rough and somewhat hilly. The hillsides were covered, much as they are today, with broken fragments of chert forming a talus. Deeper in the hills, beneath the talus, the limestone was dissolved, causing the chert beds to settle with a general dip toward the valleys. Back from the valley tracts were numerous sink-holes, caves, and caverns filled or partly filled with broken fragments of chert, which did not suffer from the general ground-water circulation. Evidently this region was at or near sea-level for a considerable period prior to the Pennsylvanian, during which time decomposition and disintegration progressed much more rapidly than transportation. Remnants of the Pennsylvanian formations occur at intervals over the entire Ozark region. They are most numerous in close proximity to the main area of Pennsylvanian, becoming less frequent as the central and southeastern parts of the Ozark region are approached. These remnants of the Pennsylvanian usually occupy depressed or protected areas in the underlying formations. The beds are usually badly disturbed and broken; as though there had been settling since Pennsylvanian time. The sandstone, which was deposited upon the residual mantle of broken flint and which probably belongs to the Chester, formed in many places a conglomerate, which, as it is found today, resembles a breccia. This conglomerate has been called the Granby. It is thought that during the deposition of the sediments of the Chester and the Cherokee, the sink-holes, underground caves, and caverns were partly filled with the bituminous clay then being deposited. The sediments of the Cherokee must have been finely comminuted—so fine that they were carried by the water circulating underground into the very minute cracks and crevices in the upper part of the Burlington. By this process the interstices between the broken chert fragments, occupying the sink-holes, caves, and caverns, were filled. It is possible that a part of the filling material of these masses of broken chert was introduced during the final stages in the removal of the Pennsylvanian, but this appears doubtful.

It is believed by some that since Pennsylvanian time, the Ozark region was almost, if not quite, base-leveled during Cretaceous time and again during the later part of Tertiary. It is possible, and indeed quite probable, that this district was covered with sediments of later age than the Pennsylvanian, but if so, these have been long since removed.

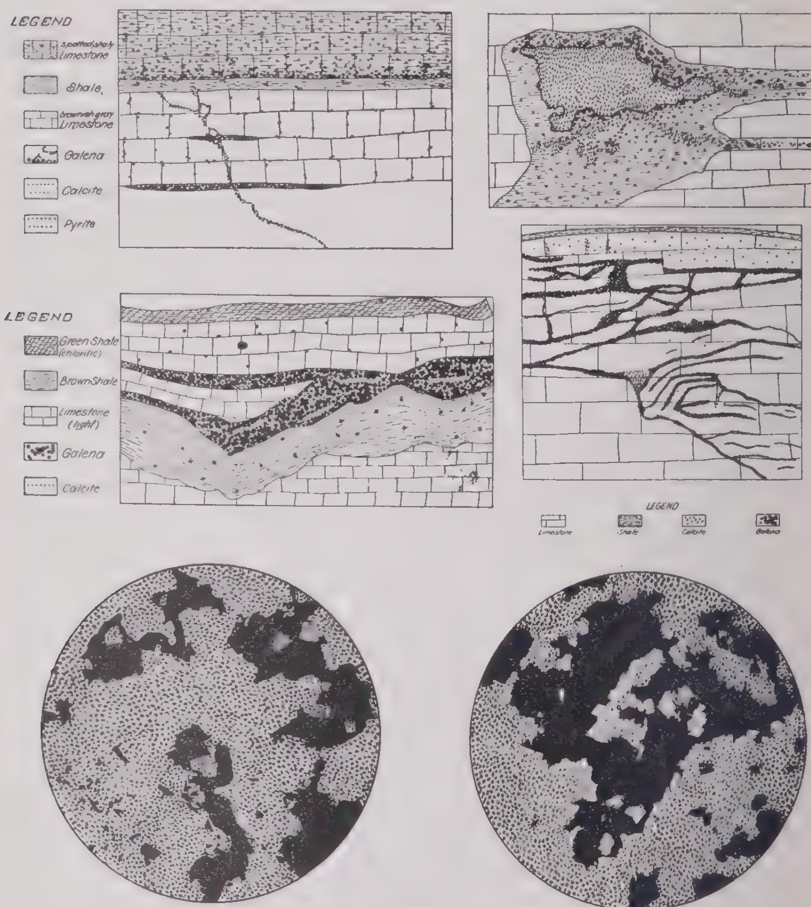
Structure.—From the eastern part of this district the formations have a general dip to the west, north, and northwest, the younger formations coming in successively in these directions. There are local dips in many places throughout the district, but these are chiefly from the hills toward the valleys, a result of the greater activity of solution along the hillsides. There is some local flexuring of the beds, but this appears to be due to original inequalities in sedimentation or to unequal settling due to solution. No faulting of consequence has been recognized in association with the ore-bodies, although minor faulting between the formations along their contact may be observed in many localities. The shale and the sandstone of the Pennsylvanian frequently occur in depressions which have resulted from the pre-Pennsylvanian erosion intervals. Subsequent solution of the underlying limestone has caused the shale and sandstone to settle deeper into the depressions, breaking the beds and producing slickensides. Some faulting of the Mississippian is reported in the vicinity of Seneca and elsewhere, but of this I have no personal knowledge. There are no chert breccias in this district that are unquestionably due to fault phenomena. As pointed out elsewhere, the breccias are mainly the result of solution and subsequent consolidation, which may have been prior to or since the deposition of the Pennsylvanian.

The most important structures in the region are the unconformities at the base of the Pennsylvanian and the Chester. These are in evidence over a greater part of the district. In some places the Pennsylvanian shale and sandstone occur a hundred feet or more below the general level of the Mississippian limestone, occupying irregular depressions in the limestone of that series. Over the entire region there are irregular areas of chert breccia, consolidated and unconsolidated, which occupy a position between the Mississippian and the Pennsylvanian. These breccias are in part pre-Pennsylvanian and in part post-Pennsylvanian. There are, however, other breccias occurring within the Mississippian which may or may not be connected with the erosion intervals between Mississippian and Pennsylvanian times. It is my opinion, however, that these breccias are all in a large measure connected with the pre-Pennsylvanian erosion intervals.

Chert is one of the most interesting materials in the district. At least three varieties may be easily recognized. The first is a white chert, devoid of fossils; the second is a white, gray, or blue chert containing fossils; and the third is a black or brownish-black chert devoid of fossils. The first two varieties are common to the limestone formation outside of the brecciated areas. The last is found almost exclusively in the brecciated areas, cementing the white or blue varieties. The lead and zinc ores of the district are pretty generally associated with the black flint. Frequently the zinc-blende is disseminated through the black chert and with it is occasionally found some galena. There is some difference of opinion as to when and how this black chert was formed. H. F. Bain has suggested that the silica from which the flint was formed may have been in a colloidal condition. I agree that some of the silica may have been in this condition, but it is doubtful if, at any time, there were any considerable masses of colloidal silica filling or partly filling the interstices between the white flint fragments. It appears more probable to me that the major portion of the silica, combined with the organic matter which gives it the dark color, was introduced mechanically in a very finely pulverulent condition. It is only necessary to point to the soft, fine grained, red clay which at the present time finds its way from the surface into the mine workings at a depth of several hundred feet, even through almost indistinguishable openings along joints, to appreciate the possibility of the silicious material of the Pennsylvania sediments penetrating the remotest parts of the Mississippian formation, in which solution prior to Pennsylvanian time may have removed the limestone, leaving accumulations of broken chert. The introduction of this bituminous silt may have been during the early stages in the deposition of the Pennsylvanian or during the latter stages in the removal of the Pennsylvanian in comparatively recent times. It is my belief that the process has been going on at both times and perhaps at some intermediate period in the history of the area, of which there is no record. The chief objection to the above theory is the absence of alumina in the chert, while the shale of the Pennsylvanian is usually rich in alumina. On the other hand, the theory of the introduction of the silica in solution is supported by the occurrence of small cavities lined with quartz crystals and the replacement of limestone by silica. It is probable that the silica was introduced mechanically, in solution, and in a colloidal state, although it is my impression that the mechanical introduction of the silica was much more important than ordinarily supposed.

Minerals.—The minerals of commercial value occurring in this district are galena, cerussite, sphalerite (also known as zincblende, jack, rosin jack, and black jack), smithsonite, and calamine. The associated minerals are greenockite, pyrite, marcasite, chalcopyrite, hydrozincite, leadhillite, anglesite, pyromorphite, malachite, limonite, hematite, pyrolusite, dolomite, calcite, aragonite, and quartz. Many beautiful pseudomorphs have been found in this area, especially in the shallow mines. The more important are smithsonite after calcite; calamine and smithsonite after sphalerite; cerussite after galena; leadhillite after calcite; and limonite after marcasite. In addition to the above minerals, there are numerous occurrences of viscous hydrocarbons, commonly called tar, which are supposed to have found their way into the limestone from the overlying Pennsylvanian, having flowed downward along cracks and crevices in this formation. In some places the tar occupies small cavities in the limestone, forming what are known as 'tar-pockets.' In the shallow mines there are frequently large bodies of a sticky, yellowish and reddish-brown clay known as 'tallow-clay.' This clay frequently contains as much as 30% of zinc oxide, and samples have been known to run as high as 41 per cent.

Manner of Occurrence of the Minerals.—The zincblende occurs in four quite distinct gangues. The first is chert; the second is dolomite, known locally as 'white' or 'pink spar'; the third is limestone; and the fourth is shale of the Chester and Cherokee formations. The two first named are the most important, the major part of the lead and zinc having been obtained from orebodies in which chert and spar are the predominating gangues. In some orebodies there is an intermingling of the spar and chert gangues, crystals of both zincblende and spar being embedded in a matrix of black chert. Cavities are of frequent occurrence in the orebodies, and these are the receptacles of masses of zincblende or galena crystals, sometimes both, with which are often associated calcite, pyrite, chalcopyrite, and other of the less common minerals mentioned above. The shallower deposits of ore consist chiefly of the spar or brecciated chert varieties, while the deeper 'sheet-ground' deposits are in a chert horizon which is more or less brecciated but shows less of the black chert, the lead and zinc minerals occurring more in the small openings or cavities which have evidently resulted from the removal of limestone which was formerly associated with the chert. In all of the orebodies there is more or less of a soft brownish-black earthy



Manner of Occurrence of Disseminated Lead Ores of Missouri. The Two Lower Figures Represent Drawings from Thin Sections Magnified About 20 Diam. (From Vol. IX., Rept. Missouri Bureau Geol. Mines. E. R. Buckley.)

deposit called 'selvage.' There is little doubt that this has been introduced into the formation mechanically by the ground-water.

In the shallower deposits near the surface galena predominated over zincblende, but in the deeper orebodies, which are now being worked, the blende predominates in the ratio of about one of galena to seventeen of zincblende. Zincblende has lately been reported as occurring in a disseminated form in the limestone underlying what is known as the sheet-ground. Outside of these lately reported deposits in the silicious limestone, the zincblende has been occasionally found disseminated through the limestone in beds higher up in the formation. The zincblende occurring in the shale of the Pennsylvanian has never been of any great commercial importance. It occurs in individual crystals embedded in the shale and is known as 'pebble jack.' With the zincblende there is frequently some galena. These conclusions assume that the orebodies near Miami, Oklahoma, are in the Chester. At this point, the deposits are in shale and sandstone, which, according to C. E. Siebenthal, belong to the Chester. Galena and zincblende are here disseminated through the rock, which is in some places heavily impregnated with petroleum. In most of the mines zincblende predominates, but in some instances galena is the more abundant of the two.

As stated above, about 65% of the galena produced by this district was mined prior to 1893, from the comparatively shallow mines worked prior to that time. Little blende was associated with these deposits, the zinc obtained during that early period being mainly in the form of calamine and smithsonite, some of which occurred everywhere with the shallow deposits of galena. In some of the sheet-ground mines little lead is obtained at present, but in most of them there is a recovery which amounts in some cases to one-fourth of the total mill product. There is very little lead in the black chert ore, there being more in the spar and sheet-ground mines. Calamine, smithsonite, and cerussite are found chiefly in the shallow mines and are undoubtedly alteration products of sphalerite and galena. Zincblende, partly altered to calamine or smithsonite, are of not infrequent occurrence. Where the original ore was a black chert in which was disseminated zincblende, the black chert is often itself decomposed, forming a porous rock known to the miners as 'cod rock.' That considerable zinc was removed during the process of alteration is evidenced by the frequent occurrence of pseudomorphs of smithsonite after calcite, and the occurrence of stalactites of cerussite in the shallow mines. These are usually associated with considerable 'tallow clay,' and occur mainly at a depth of less than 100 feet.

Ground-water.—Some of the mines in this district are dry, while others are very wet. There has been no attempt to measure the amount of water pumped from the various mines, but instances are known where from a depth of about 250 ft. as much as 500 gallons per minute have been pumped. This amount is, however, exceptional. In some parts of the district the water is very acid, so much so that it is impossible to use iron pipes with any degree of economy. The water in the mines is mainly, if not entirely, derived from the surface circulation, there being no well authenticated case where the water comes from a deep or artesian circulation. There are deep wells in the district, one of which, at Carthage, has a depth of 2005 ft. This well is reported to have penetrated granite at a depth of 1750 ft. Most of the deep wells do not exceed 1000 ft., penetrating, at this depth, a portion of the Cambrian formations.

The waters from several of the mines and from some of the deep wells have been analyzed in the laboratory of the Missouri Bureau of Geology and Mines, with the results shown in the following table. The water from the surface circulation was not in all cases shut off from the deep water in the wells, which would permit the introduction of some lead and zinc salts by the mingling of these waters.

ANALYSES OF WATERS FROM MINES AND DEEP WELLS OF THE JOPLIN DISTRICT.

	Captain mine.....	Deep well at Carthage	Deep well at Alba.	Deep well at Providence mine	Yellow Dog mine..	Arkansas mine at Prosperity	Victor mine	Deep well at Webb City	Winslow mine....
KCO	16.2	1.0	3.0	0.0	0.0	9.5	6.1	3.2	4.0
K_2SO_4	11.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.2
NaCl	0.0	3.6	8.4	2.8	8.1	0.0	1.3	0.7	0.0
Na_2SO_4	198.0	15.7	9.6	15.4	82.5	130.3	38.5	13.2	14.7
$Al_2(SO_4)_3$.	87.2	1.7	3.0	0.0	5.4	68.3	73.6	0.0	2.2
$CaSO_4$	2044.8	0.0	12.6	7.7	909.7	1528.0	924.6	2.2	59.7
$Ca(HCO_3)_2$.	62.2	141.8	303.7	152.4	0.0	0.0	0.0	158.3	250.6
$MgSO_4$	572.4	0.0	0.0	0.0	37.6	Trace	192.6	7.5	0.0
$Mg(HCO_3)_2$.	0.0	96.4	37.2	105.1	49.6	0.0	0.0	0.0	0.0
$FeSO_4$	513.0	0.0	2.1	1.9	4.4	611.9	387.7	1.3	6.4
$Fe(HCO_3)_2$.	0.0	2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$ZnSO_4$	557.8	0.0	1.7	0.0	92.7	586.2	851.7	0.0	0.0
$Zn(HCO_3)_2$.	0.0	4.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$CuSO_4$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$PbSO_4$	0.03	0.0	0.0	0.04	0.043	0.04	0.0	0.0	0.0
SiO_2	14.3	9.1	12.3	16.8	10.1	23.2	23.2	11.9	11.3
H_2SO_4	0.0	0.0	0.0	0.0	0.0	170.9	251.7	0.0	0.0
CO_2	234.0	11.9	4.8	0.0	11.0	12.0	87.0	0.0	8.8

Weights in parts per million. (V. H. Gottschalk, Analyst.)

It will be observed from an examination of this table that very little lead or zinc, and frequently none, is found in the waters from the deep wells, while the waters from the mines in every case contain appreciable quantities of both metals. Special attention should be given to these analyses, since they have an important bearing on the question of genesis.

Genesis.*—All the evidence that I have been able to gather seems to indicate that the orebodies from the first to the latest concentration are mainly the result of converging, downward circulating waters, the oxidizing portions of which carried the metallic salts in solution and the reducing portions of which carried the organic matter which provided the precipitating agent. It is probable in many instances that there was only the oxidizing circulation, the reducing conditions being supplied by the organic matter contained in the chert breccias and in the openings caused by the removal of the limestone. There are numerous deposits of galena and zincblende in the southern part of Missouri which can hardly be accounted for except through the disintegration and decomposition of the Pennsylvania shale and limestone. In Miller county alone there are eight or ten small, isolated areas of Pennsylvanian shale in which galena and zincblende are found. These minerals occur either along the contact of the shale and the underlying magnesian limestone, or filling joint and bedding planes within the shale and coal. There are many similar occurrences of zincblende and galena in the areas of Pennsylvania shale and coal in Moniteau, Cooper, and other counties in the central part of the State. The ground-water, passing through these isolated areas of shale and coal, has had no recognizable avenues of communication with the deep ground-water circulation. The orebodies do not extend beyond the influence of the solutions passing downward or laterally through the coal pockets. In fact, every condition leads to the conclusion that these lead and zinc minerals have been brought to their present position by downward circulating waters.

As pointed out by C. R. Van Hise and others, the ultimate source of the metallic minerals was probably the igneous rocks. From the time these metals were abstracted from the igneous rocks to the time they attained their present position in orebodies in the Mississippian, they may have been several times, in part, at least, precipitated from oceanic waters and redissolved through the weather-

*See 'Geology of the Granby Area', Missouri Bureau of Geology and Mines, Vol. IV, 2nd Series, 1905, by E. R. Buckley and H. A. Buehler.

ing of the land when such sediments became a part of the continental land area. As explained on a previous page, lead, zinc, or any other metal which may be contained in a formation which is being decomposed and removed from the surface, will eventually be disposed of in two ways; (1) by removal in streams to the ocean; (2) by transference through ground-water to greater depths. In the first case the metals are precipitated from the sea water and added to the sediments wherever favorable conditions for precipitation may occur. In the second case the metallic salts are concentrated within the underlying formations wherever these formations supply the necessary reducing conditions. These processes have been in operation since the continents were born and during each successive erosion interval there has been a concentration of the metals through the downward movement as well as a concentration in the sediments being deposited along the shores of the continents. If the ocean does not supply these conditions near the mouths of streams, a wider distribution of the salts may result.

In the geological history of this region no conditions are known more favorable to the deposition of the metallic salts contained in the ocean or emptied into the ocean by streams, than those that existed during the Pennsylvania period. Almost everywhere there must have been conditions simulating those by virtue of which these metals are now being concentrated within the Mississippian formation. The occurrence of galena, sphalerite, pyrite, and marcasite, the latter in great abundance, with the Pennsylvanian, in many parts of the region, is strong evidence that the metals were thrown down abundantly in some portions of the Pennsylvanian sea. It is a noticeable fact that the pyrite is most abundant in the coal and shale where they occur near what is supposed to have been the shore line. It is more than probable that the metals contained in the oxidizing waters from the land areas, at that time, which were collected from broad catchment areas, were precipitated before traveling far from the shore. This would tend to localize, within the Pennsylvanian, the original deposits. Later, in the Pennsylvanian sea, when the reducing conditions became more general or the land area was completely submerged, the distribution of the metallic salts would become more general, and when the source of the supply was cut off, their introduction would cease.

If the estimate that 0.002% of lead and zinc throughout the Cambrian rocks of the Ozark region would be adequate to account for all the ore deposits of the region, then very much less would be required in the case of the Pennsylvanian, since, through the almost complete removal of this series from the area in which these ore-bodies occur, all the lead and zinc that they at one time contained, must have been transferred to other places. On the one hand the extremely favorable conditions for the precipitation in the Pennsylvanian sea leads to the supposition that the localization or concentration of the original precipitates would be many times greater that in the Cambrian sea.

In a consideration of the ore-deposits of the Mississippian the starting point must be the last time the major part of the lead and zinc was held in solution by the waters of the ocean. In the case of this district, it is thought to have been the Pennsylvanian. It is believed that the concentration from this formation into the Mississippian has resulted from solution and redeposition, as a result of weathering, in the manner above described. Evidently there has been a movement of these minerals, downward, as the degradation of the land proceeded. That this process is still in progress is shown by the growth of lead and zinc minerals in mines of the district that have been abandoned and flooded with water, and by the occurrence of lead and zinc salts in the mine waters. On the other hand, the absence of deep-seated faulting and the fact that the waters of the deep wells contain little if any lead or zinc in solution argue against the artesian theory of the origin of these ores. It is also very probable from an analysis of the historical conditions that during the pre-Pennsylvanian erosion intervals some lead and zinc was concentrated in the Mississippian. This would later have been removed from the zone of weathering by the submergence of the land by the Pennsylvanian sea.

The entire process of ore-deposition in this district has been one of enrichment below the level of ground-water, brought about by the migration of the metals downward. The process has been one of constant but interrupted concentration, the interruptions being due chiefly to changes in the level of ground-water resulting from successive periods of elevation and subsidence. This conclusion agrees, essentially, with that of W. P. Blake, announced for the origin of the Wisconsin lead and zinc deposits. He says: "The evidence is strongly in favor of the view of the long-continued decomposition, downward flow, and recomposition of not only the ores of zinc, but lead and of the pyrite from the upper formations to the lower, as the general level of the region subsided and as the upper formations by long continued exposure through geologic ages were gradually decomposed in place."

Above the level of ground-water, and in many cases far below, a process of abstraction is going on, as a result of which the sulphide minerals are in part taken into solution and in part altered to the carbonate and silicate. The carbonate and silicate are in many places precipitated as such from the underground waters, replacing the limestone and calcite crystals, forming stalactites in caves and caverns, and lining the small openings within the chert. In some instances the introduction of silica has followed the formation of the zincblende, as shown by the occurrence of quartz crystals superimposed upon a layer of zincblende. Casts of crinoids and brachiopods, lined with rosettes of calamine, have been frequently observed. It is noticeable that the removal of the sulphides and silicates from the zone of weathering to the deeper levels has in many places lagged behind the surface weathering. Especially is this true of the galena and carbonate minerals which, in the Aurora, Granby, and other areas, have been found in their greatest richness near the surface, often at the grass roots.

CENTRAL MISSOURI DISTRICT.

In the central Ozark region, in formations younger than the Potosi and older than the Ordovician, but occasionally associated with pockets of Pennsylvanian shale and coal, occur deposits of lead and zinc ores, some of which produced prior to 1855 as much as 5000 tons of galena. The ores of commercial importance occur in different formations from those in which the ores of the Southwestern and Southeastern Ozark districts are found. The Central Ozark lead and zinc-bearing formations are chiefly the Gasconade, Roubidoux, and Jefferson City, which differ in their composition and in the manner of occurrence of the lead and zinc minerals, and are in many other particulars different. The pockets of Pennsylvanian shale in this district rest chiefly upon Cambrian dolomites, while in the Southwestern district they rest upon Mississippian limestone. There are also outliers of Mississippian limestone resting unconformably upon the Cambrian dolomites and often associated with the pockets of Pennsylvanian shale and coal. The pre-Pennsylvanian erosian interval did not produce extensive chert breccias or the extensive underground solution in this region that it did in the Southwestern district, probably due to the difference in the composition of the formations exposed at the surface. For this reason the

Cross-Section of Ozark Region: Position Shown on Map.

orebodies of the Central district are more restricted in size. There is some folding and faulting in the Newburg area in which prospecting has been carried on for a number of years, which is especially noteworthy. The Central Ozark ore deposits contain both lead and zinc, but in addition there is barite, which is very rare in the Southwestern district. The chert breccias do not contain the black chert which so generally characterizes the ore deposits of the Southwestern district, and the spar is of much less frequent occurrence. Besides occurring in chert breccias and associated with the Pennsylvanian shale and coal pockets, the ores are found, especially in Franklin county, in veins which are known to have a depth in some instances of several hundred feet. The vein on which is located the old Virginia mines produced more than 5000 tons of lead, and the production of the vein on which is located the mine of the Bellew Mining Co. makes it worthy of special mention. However, these mines are not comparable, in production, with those of either the Southwestern or the Southeastern Ozark districts. In Taney county, Missouri, there is a fracture zone about eighteen miles long in which occur deposits of lead and zinc ore. Although prospecting has only been carried on near the surface the relations exhibited by the formations indicate only minor faulting. In the coal and shale pockets of the Pennsylvanian of this district, there are thin sheets of sphalerite and galena, the former occasionally having a thickness of nearly an inch.

The ores of this district have had an origin similar to that described for the other two districts. They belong to the descensional class, having resulted from the concentration of the lead and zinc in favorable places by downward circulating ground-water, these metals having been derived from formations which at one time overlay those at present occurring at the surface.

THE MISSOURI-ARKANSAS DISTRICT.

This district lies almost wholly in Marion and portions of Searcy, Baxter, Newton, and Boone counties, Arkansas, but extends northward into Missouri and should include Oregon, Ozark, and Taney counties of the latter State. This section of the Ozark region is rugged and hilly, being well drained by the White river and its branches. The principal city in the district is Yellville, and the Arkansas portion of the district is frequently spoken of as the Yellville district. The ores of this district were discovered prior to 1818, and since that time the output of zinc concentrate has been about 13,600 tons. The output of lead concentrate has been much less. It is thought that the total output of lead and zinc from this district has been less than that from the Central Ozark district.

In this district the ores occur chiefly in the Yellville formation, which E. O. Ulrich considers to be of Ordovician age. The formation is above the dolomite formations in which occur the lead and zinc ores of the Central Ozark district, being above the Jefferson City dolomite and below the St. Peters sandstone, known in Arkansas as the Key sandstone. Ores also occur in the Burlington (Boone) formation, but the importance of these deposits is less than that of the orebodies in the Yellville formation. The zinc minerals are mainly sphalerite, smithsonite, and calamine, while the lead minerals are galena and cerussite. Other less common lead and zinc minerals occur. Up to the present time the chief production has come from the smithsonite, calamine, and zincblende. These minerals occur in limestone and chert breccias and along fault zones. The ores outcrop at the surface in many places and are frequently reached by adits.

From such observations as I have made in the district, I am led to believe that the breccias not associated with faulting are due to some mechanical process not as yet clearly understood. These 'hillside' breccias frequently die out as they are followed into the hill, which leads to the supposition that the entire bed of which they form a part was not involved in the movement, or whatever it may have been, which resulted in their formation. Galena is a subordinate constituent of the orebodies, although constituting the entire product of a few of the mines. Zincblende, smithsonite, and calamine are associated in the ores, even at the surface. The zincblende is very pure, there being a noticeable absence of the iron sulphides. The zinc minerals are frequently associated with an abundant gangue of spar as in the Joplin district.

It is believed that the ores of this district belong to the descensional class, having been concentrated in their present form from descending circulating ground-water. As stated by J. C. Branner, "The position of the ores in the secondary deposits has been determined largely by those structural features that have guided the underground waters in their passage through the rocks." I would add that the deposition in these places was probably further controlled by the presence of conditions necessary for the precipitation of the lead and zinc salts from the ground-water. Banner says further, "The accumulations of ores have taken place sometimes along synclinal troughs, sometimes in fissures along fault planes, and sometimes in the breccias formed along other ancient underground water courses." As in the case of the Southwestern and Southeastern Ozark district, this region was probably at one time overlain by the Pennsylvanian formations. This series reaches nearly to the area included within this district, outliers being included within the district as mapped by the United States Geological Survey. It is natural that I should see in the proximity and probable extension of these deposits over the district, the same relations between them and the ore deposits as have been outlined on the preceding pages for the other districts of the Ozark region.

NATIVE COPPER DEPOSITS.

By ALFRED C. LANE.

*Native copper occurs in various places as a casual alteration product of sulphide deposits, in which case it is not the important ore, being simply a rare accessory. There are, however, regions in which native copper is the essential ore. By far the most famous of these is that of Keweenaw Point, off the south side of Lake Superior, in Michigan. Native copper also occurs in various places around Lake Superior besides Keweenaw, as, for instance, on Isle Royale, on Mamainse Point, and Michipicoten Island. But there are other regions in which native copper occurs as the characteristic ore mineral. The mines of Corocoro in Bolivia have recently been described by Steinmann.[1] It was also the ore mineral of the Colonial Copper Co. at Cape d'Or, on the Bay of Fundy, and it is found along the Connecticut valley and from the palisades of the Hudson to Maryland. I have seen a sandstone from a Western locality which was cemented together by native copper. I am also told that in the famous melaphyre region on the west bank of the Rhine about Oberstein, where many so-called Lake Superior agates have been polished, native copper has been found.

It may be well to call attention to certain characteristics which these deposits have in common.

1. They all occur in connection with red sedimentaries in the Saar region; the Triassic—(and to some extent, the Permian)—the well-known red sandstone of the older geologic writers. When the Lake Superior deposits were first studied they were in appearance so much like those of the Saar region that by some writers they were attributed to the same period. The associated sandstone is also red in Bolivia.

2. The deposition of the copper in all cases, I believe, is attended by a blanching of the sandstones. Whether this is due to an actual

*Read at the annual meeting of the Canadian Mining Institute, Quebec, 1911, and republished by permission.

[1]Fest schrift. Harry Rosenbusch, p. 335. R. Harris, of the Canadian Institute, who has personally examined the deposits, gives me the same information.

removal of the ferric iron or to its reduction to a ferrous iron, or to ehe development of some mineral like epidote, which, though it contains ferric iron, is not red, I will not pretend to say.

3. This formation of red sediments is also associated with basaltic dark-colored lavas containing a large amount of ferrous iron and a small percentage (about 0.02%) of copper. This quantity of copper is on the whole quite uniform, since it is found not only in F. F. Grout's average analyses reported in *Science*,[2] but also in Laspeyres' analysis of rock from Norheim tunnel.[3] It is also the approximate percentage of copper found by myself as the average result of tests on the sludge from some 6000 ft. of drilling across the Keeweenaw range. The commonest type of these basaltic lavas seems to be very close to that which years ago Bunsen, in studying the lavas of Iceland, described as the normal basalt, which I have given reasons to believe[4] is in composition the most fusible of the common series of rocks.

4. I should like to add another point, about which I cannot be so certain, and I add it rather as a suggestion. In all cases native copper was associated with waters containing a high percentage of earthy chlorides. This is not true as regards the surface rocks where the salty water has been leached out; but the peculiarly saline character of the deep water from the Keweenawan rocks of the copper mines is now well established.[5] Steinmann refers to the salty character also of the Bolivia mines, and certain analyses of deep wells in New Jersey suggest that a similar water is found in the Triassic there, while Laspeyres gives an analysis of water from Durkheim[6] which seems to suggest that a similar water is associated with the German melaphyre.

5. The native copper is not usually found in fissure veins, although it does occasionally so occur. It is characteristically irregular, and of the nature of a replacement or an infiltration of the surrounding country rock.

6. Another point of resemblance, not absolutely universal, is the association with zeolitic minerals characteristic of the traps which contain water and which, there is good reason to believe, were deposited from hot water.

So much is fact. These facts can, I think, perhaps be welded

2 *Science*, Sept. 2, 1910.
3 *Zeits. d. geol. Ges.* 19, p. 855.
4 'Wet and Dry Differentiation,' Tufts College Studies, Vol. 1, Pt. 3, p. 40.
5 *Proc.* Lake Superior Min. Inst., 1906, 12, p. 154.
6 *Zeits. d. geol. Ges.*, 20 (1868), p. 191.

into a consistent theory, one that will be at the same time somewhat suggestive as to where to look for the copper.

The formations in which native copper occurs are those which, according to the general belief of the geologists, were formed at periods when the land stood high and the ocean relatively low. Moreover, red rocks have by many geologists been considered to have been largely laid down upon the land. This seems natural, because there would then be more chance for oxidation of the iron. There are, however, exceptions to this rule. If we take the admirable series of geographic maps of the North American continent issued by Charles Schuchert, we find that at the time of the Lower Cambrian, say the Upper Georgic, most of North America was out of water. And yet Lake Superior was then, as now, a great basin, and it would seem probable that deposits would have gone on forming in this basin even during the considerable elevation of the continent which took place after deposition of the pre-Cambrian rocks, and before the great depression of the continent and consequent overlap that produced the sandstone formation popularly designated the Potsdam. My present interpretation of the Keweenawan formation is, that during this interval when most of the continent was out of water, in the early Cambrian (and perhaps somewhat earlier), the copper-bearing formation of Lake Superior was laid down as a great series of lavas and red beds like those which now occupy many places in the Great Basin region; the great plains of the Snake river in Idaho, for example. Another characteristic of the Keweenaw sediments is that so large a proportion of the material is derived from the formations themselves. The conglomerates are often composed of amygdaloid pebbles which have apparently originated from the amygdaloid formation, and the fact has been recognized that the Calumet & Hecla conglomerate material at Calumet came very largely from a quartz porphyry of the Keweenaw formation exposed not far distant. A couple of miles south its lithological character has entirely changed. In such a great interior continental basin the erosion took place that produced these sediments, and that erosion may also have leached out the copper contained in the traps. This copper may have remained in solution as copper chloride in the waters buried in the more porous beds and may have collected, possibly, in extra richness in certain pools in the desert. If these pools were invaded by lava streams, as certainly at times happened, the water would be evaporated and a further concentration might proceed. Thus it can be imagined that the formation came to be filled with saline waters containing chlorides of copper derived either from the volcanic eruptions in the first place, or from the decomposition of lavas later, and possibly concentrated still further by the evaporation of those waters either by the heat of the sun or by that of lava flows before the sediments were buried. Such a formation would not lose all its heat for a long time. Calculations have convinced me that after a million years nearly half might remain undissipated, and that even after fifty million years the disarrangement of the gradient of temperature in the earth would still be very appreciable. As the formation slowly cooled, however, water would be sucked in. Lake Superior is a great basin, and the Keweenaw strata dip toward the centre of that basin on all sides, so that in any such absorption of water there would be a tendency for the water to migrate toward the centre, independent of any artesian circulation which also might well have been set up, and of the hydration which also took place.

How, then, was the copper deposited? Experiments have shown that in an unequally heated solution of copper and other chlorides the copper will be deposited at the hotter end if the solution is kept alkaline. If, therefore, in such a case the copper solutions can find some rock which will tend to keep them from being oxidized, and at the same time remain alkaline, there is no reason why copper should not be deposited.

The reactions by which the copper was precipitated have been discussed by Fernekes.[7] It appears that an unequally heated chloride solution will tend to precipitate copper toward the hotter end, if the solution is kept alkaline. Both desert waters and lavas and rock powders generally are alkaline. Suppose their alkali be represented schematically:

$$2\begin{pmatrix}\mathrm{Na\ Si_4O_9}\\ \mathrm{Ca\ SiO_3}\end{pmatrix} + 2\,\mathrm{Cu\ Cl_2} + \begin{pmatrix}\mathrm{C}\\ \mathrm{2\ FeO}\end{pmatrix} = \mathrm{Cu} + 2\begin{pmatrix}\mathrm{Na_2}\\ \mathrm{Ca}\end{pmatrix}\mathrm{Cl_2} + \begin{pmatrix}\mathrm{4\ SiO_2 + CO_2}\\ \mathrm{SiO_2\ or\ F_2O_3}\end{pmatrix}$$

The deposit of the oxygen by union with ferrous iron, as advocated by R. Pumpelly, no doubt occurs at times at the other pole of the solution, but I am now inclined to lay stress on the reducing carbon gases proved to exist in these lavas by R. T. Chamberlin,[8] and assumed for lavas generally by Brun.[9]

Calcium chloride, into which the carbonates may have gone, is intimately associated with the copper. The silica of the above reac-

[7] *Economic Geology*, 2, No. 6, pp. 580-584, 1907.
[8] 'The Gases in Rocks,' Carnegie Institution, 1908.
[9] 'Recherches sur L'exhelasison Volcanique,' 1911.

tion appears in the abundant secondary quartz and the sodium and calcium chloride are characteristic of the mine water.

As a matter of fact, there is a strong tendency in the Lake Superior district for the copper to occur near channels that may be considered to have been once pervious, such as conglomerates, or porous beds of lava flows and fissures. But there is also a strong tendency for the copper to occur rather at the sides of the pervious channels in the country rock and adjacent to, rather than in, the main channel. In other words, the mode of occurrence is suggestive of a contact deposit occurring in a pervious bed or in its immediate neighborhood and filling fissures and joints in a less pervious bed. The traps overlying the copper-bearing conglomerates show films of copper upon the joints, and the copper-bearing amygdaloids must be followed with considerable care, or highly valuable deposits of native copper stretching off into the foot-wall will be overlooked.

If the theory above outlined is true, the fact that copper is quite likely to occur, not in cross-fissure veins, but in beds, extending for miles with the layers of the formation, can be easily explained. Take, for example, the so-called Kearsarge lode. This is the amygdaloidal trap of a very peculiar flow or group of flows. It has been mined commercially for fourteen miles, and to my knowledge contains noteworthy amounts of copper for two or three times that distance. This flow occurs immediately on top of a fine grained sandstone or shale of a deep red color. This is the type of deposit that might be expected to form in one of those desert plains or basins to which attention has recently been called by students of physical geography who are familiar with the work of wind erosion and deposition in the West. If over such a plain, or a lake occupying part of such a plain, a lava stream should flow, it can readily be seen that the copper salts derived from the degradation which produced all the sandstone would be concentrated in the porous parts of the lava flow. It can also be easily seen that this concentration would be followed by further enrichment if by the upheaval of the formation the waters were set circulating downward and reacting upon the lava flow, thus precipitating the copper wherever the solution was sufficiently hot and alkaline to favor it. Again, one can understand why antimony is so extremely rare in connection with native copper (since the presence of a little chloride salt in an electrolytic solution operates to prevent antimony being thrown down with the copper), and why the copper is produced from chloride solution. The association of the silver can also be explained.

for, while silver chloride is generally classed as insoluble, it is sufficiently soluble in these salt solutions to accompany the copper to the extent noticed. In the reactions which produce the copper, as stated, the solution must be kept alkaline, and that alkalies should go into solution may therefore be expected. As a matter of fact, plain indications are found of copper having replaced rock, such as the pebbles of the Calumet conglomerate, and of sodium silicate and similar substances having been dissolved, sodium accumulating in the mine water. It should be said, to avoid obvious criticisms, that copper ores do indeed occur in the Keweenawan formation, but in many cases they seem to be produced after the main deposition of copper. The wonder is not really that occasional sulphides and arsenides of copper occur, but that so little sulphur and arsenic is found. Nor would it be wise to say that copper does not occur or may not occur in commercial quantities in the Lake Superior mines in fissure veins, for it has been so found in times past. The next great copper deposit may very well be a type somewhat different from any one heretofore developed. It may be a stockwork in a fissured felsite. It is perfectly possible that at times the course of the currents which tended to concentrate the copper was lateral or downward, and cross-fissures would certainly tend to promote circulation which would facilitate the concentration of the copper into deposits of commercial grade. As a matter of fact, the bedded lodes are sometimes richer near certain fissures. This was particularly true in the Central mine, where not only did the vein contain copper, but the various amygdaloids near the vein contained copper.

Two points which, I consider, are really of some practical value are (1) that in testing or working such deposits of native copper the vein or main channel of circulation may be taken as the leader, but that deposits of copper running off into the walls should be expected; (2) that if I am correct in associating the deposits of the copper with the chloride solutions, so long as the water is fresh, it is not unreasonable to expect a greater accumulation of copper below. This may or may not have taken place, according to the direction of circulation. After the saline waters have been struck and fairly established, it is probable that the rock will not become richer with depth. For instance, the Calumet & Hecla mine was probably at its best somewhere between 2000 and 3000 ft. from the surface.

The question of exploring such regions as characterized by the features described, and not merely fissure veins, should be studied, particularly the places where pervious or impervious beds come in contact and where rocks of very different chemical character occur. To apply this, for instance, to the region of the Bay of Fundy, it would seem that some attention should be given, not merely to the fissure veins which cut the great traps, but also to the place where these trap flows come in contact with underlying red beds.

It will be noticed that, according to Schuchert's maps (51), just at the time of the early Cambrian, the North American continent stood relatively high. So also at the time of the Triassic (86), the continent was high, and the deposits of the Triassic of Nova Scotia were in a basin far separated from the sea. The deposits found by investigating these contacts may not be of commercial value, but there is a good degree of probability that there will be some enrichment, and in particular it would seem that if any encouragement is found, the test by diamond-drilling or otherwise at a very considerable depth, sufficient to see whether these chloride waters which I have assumed really occur there, ought to be undertaken. Until this is done I, at least, would not be ready to give up hope of commercial deposits. The amount of copper which can be picked up along the beach of Cape d'Or is due largely to the marine erosion attacking some amygdaloids which dip toward the ocean. Whether these amygdaloids, if struck somewhere deep down under the Bay of Fundy, would be found to have copper in abundance, and whether the contact of the series of traps with the red Triassic beds beneath would show copper, are questions which the explorations so far conducted have not answered.

COBALT DISTRICT, ONTARIO.

By S. F. Emmons.

*Doubtless most of you are more or less familiar with the general geological relations of the Cobalt district as given by the Canadian geologists. My own examination of the district has been too brief and cursory to justify any criticism of their determinations, which I therefore accept as far as the areal geology is concerned. The ore deposits are, however, of so remarkable a nature and so utterly different from anything seen within the boundaries of the United States that I have thought it might be interesting to you to hear what particularly impressed one who has had considerable experience in the study of the latter. I will begin with a brief statement of the facts thus far determined by the Canadian geologists, since some of you may not have had occasion to inform yourselves with regard to them.

The Cobalt district lies in the rugged region known as the Archean protaxis, about 330 miles due north of Toronto, midway between Lake Ontario and Hudson Bay. Rich ores were first discovered in the district in 1903, as the result of the building of the Government railroad, known as the Temiskaming & Northern Ontario, northward from North Bay on the Canadian Pacific railway. Yet the district is on an old traveled route, and an argentiferous galena deposit had been worked on the shores of Lake Temiskaming, eight or nine miles to the eastward, over 160 years ago, and which shows how readily valuable deposits of the precious metals may escape observation.

Two geological maps are published by the Department of Mines of Ontario, the smaller, the Temiskaming sheet, covering an area of 15 miles square, on a scale of a mile to the inch, with Lake Temiskaming on the eastern half, and the Cobalt district a little south of the centre. The larger represents the Cobalt district on a scale of 400 ft. to the inch, with a contour interval of 10 ft. The geo-

*Read before the Geol. Soc., Washington, January 26, 1910, and published in the *Mining and Scientific Press,* March 18, 1911.

logical colors on these maps represent the following formations, commencing with the older:

Keewatin is the oldest pre-Cambrian formation, and consists of an igneous complex, largely altered diabase and basic tuffs, intruded by granite, in the southwest portion of the area.

Lower Huronian.—Unconformably on these lie the Lower Huronian rocks, consisting of conglomerates and graywacke (slate or altered quartzite), which contain fragments of the older series. These are separated by another unconformity from the next higher.

Middle Huronian.—A series of arkoses (or 'green quartzites') with conglomerates and quartzite, which rest unconformably on the preceding.

Diabase.—All the above mentioned rocks are cut by intrusive diabases which are hence assumed to be of pre-Cambrian age. A great unconformity, representing a long period of erosion, separates the preceding rock from the succeeding rocks.

Niagara limestone, which is found on the shores and islands of Lake Temiskaming. The area is one of many patches of Paleozoic rocks that seem to have escaped erosion, because of being included in a synclinal depression of the ancient surface.

The more common minerals of the rich vein deposits are the arsenides of cobalt and nickel, smaltite with some chloanthite, cobaltite, and niccolite, associated with native silver. Less frequent are native bismuth, the silver minerals pyrargyrite, proustite, dyscrasite, and argentite, the nickel sulphide, millerite, with occasional mispickel and tetrahedrite. The ordinary sulphides, pyrite, galena, and zincblende, are occasionally found in the wall rocks, but apparently do not form an essential part of the deposits. The gangue minerals are calcite with a little quartz, but both are in relatively subordinate amount in the rich parts of the veins. Minute calcite veins are common throughout the rocks of the district and often serve as leaders which are followed in searching for pay-ore. On the surface the cobalt veins are traced by the delicate pale reddish-blue color of 'cobalt bloom' (the hydrous arsenate of cobalt) which is the oxidation product of the cobalt minerals.

The veins in which these minerals are found are remarkably narrow, being from one or two inches up to eight inches in width, and in exceptional cases more than a foot for short distances. They are generally nearly vertical, but seem to be rather irregular in strike. In some cases the pay portions bend almost at right angles; in such cases as came under my observation this was caused by the mineral leaving a fissure of a given strike to follow one running in another direction, the first fissure continuing on, though barren of ore. The linear extent of the pay portions of the veins is not great, generally not over a few hundred feet, but the actual extent of the fissure is evidently much greater. How much could not be determined, as they are often simple lines of barren calcite, which are not followed for any great distance. In depth it was soon found that the very rich ore, which carries from 2000 to 6000 oz. per ton, does not extend, as a rule, more than 200 ft. in depth, often not as much, and the first generalization of the Canadian geologists was that the Lower Huronian conglomerate is the favorite *habitat* of the rich silver ores, and that they cease when the vein reaches the underlying Keewatin, which was explained as due to the physical character of the rocks of that formation, which do not fissure as readily as the Huronian. As prospecting was therefore mostly carried on in the rocks of this formation, a larger percentage of vein deposits has been discovered in it than in the other formations, but, as I shall show later, this does not seem at present to be the most probable explanation, an increasing number of pay-veins being found both in the diabase and in the Keewatin.

As to the origin of the fissures, the idea has been more or less prevalent that they are the result of contraction, because in many places they resemble joints, and show no slickensided surfaces. On the other hand, it is recognized that they run continuously from the Huronian into the underlying Keewatin, which are separated by a great unconformity. On this point, W. G. Miller, the geologist of this region, after calling attention to the fact that the fragmental Huronian rocks have been less disturbed in the productive area than in the surrounding regions, says: "This left them in the right physical condition to be readily jointed and fissured by the contraction of the diabase." As to the genesis of the minerals, they have been assumed in a general way to have been connected with the post-Huronian diabase eruption. There are said to be diabases of several ages from Keewatin to probable Keweenawan. The post-Huronian diabase carries some quartz. Miller says: "After the deposition of the cobalt-nickel arsenides, the veins appear to have been slightly disturbed, giving rise to cracks and openings in which the silver and later minerals were deposited. Veins which escaped this later slight disturbance contain little or no silver.'' A granite or aplite dike cutting diabase is found within the Cobalt area, on the north shore of Giroux lake, on the University claim, and outside this area aplite is more frequent in similar association, and is said to carry cobalt, whence it has been assumed that the aplite, which constituted the last phase of the diabase eruption, was the mineral carrier. C. R. Van Hise considers that the diabase body in the Cobalt area is in thin sills and hence does not extend deep; basing his assumption on the fact that the rocky beds that it intrudes are not upturned or pushed back, but comparatively undisturbed. This assumption has been in a measure confirmed by the finding, either by shaft-sinking or drill-holes, of underlying rocks at one or two points within a few hundred feet of the surface. It is generally recognized that the native silver is of distinctly later deposition than the cobalt-nickel arsenides—indeed, the evidence in the mines is most conclusive. In one case I observed a distinct narrow vein carrying native silver and calcite that crossed the mass of cobalt ore at a slight angle. Very often minute cracks may be seen crossing the cobalt mineral and gangue rock which are filled with films of native silver, and the flake or sheet form in which the silver is so often found, shows that it has grown in such cracks. That, however, the silver, as a whole, is of a distinctly later period of deposition, as seems to have been assumed, I am inclined to doubt. At any rate, it does not appear to be, as yet, definitely proved.

My own visits to the district have been too brief to admit of an exhaustive study, though I was able to see one mine pretty thoroughly and visit one or two others, so that what I have to say is rather tentative than final. The early mining, owing to the novel character of the deposits and the want of experience of most of those in charge of mines, was not very systematic, being largely in the nature of trenching on the surface and digging out the rich ore immediately in sight. Systematic exploration by underground driving and cross-cutting is a comparatively recent feature of the work. I was, however, fortunate in visiting a mine that had been developed by an engineer of long practical experience in managing large mines in Colorado, in which the facilities for underground study were in consequence exceptionally good. This is the Kerr Lake mine, which occupies a tract of 57 acres, part of which is under the lake. In spite of the relatively small area of the property, this mine has proved one of the most productive of the district, having thus far developed five remunerative veins, to say nothing of a host of small veins, as yet of no great producing capacity, but which may any day develop pay-shoots. Singularly enough, the largest orebodies, with one exception, thus far developed, have been under

NORTH-SOUTH No. 7 VEIN; 90-FT. LEVEL; 12 INCHES WIDE; KERR LAKE MINE.

the waters of the lake, which is also the case with the adjoining Crown Reserve mine. This fact has led some of the mining men to think there is some genetic cause which renders the ground under the bottoms of the many lakes that dot the region peculiarly favorable for the concentration of rich ore, and the rights to mine under these lakes have been purchased from the Government at very high prices; in one instance, I believe, for over a million dollars.

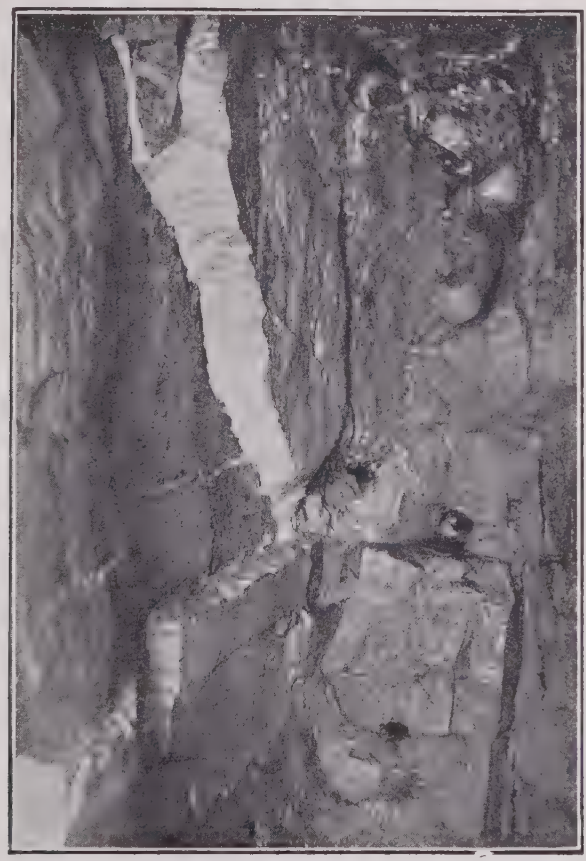
The exceptional character of mining in this district, and the favorable results of a good system may be shown by extracts from the annual report of operations of this mine for the year ended August 30, 1909. The gross product for the year was 2,668,648 oz. of silver from shipments of 1072 tons of ore and 300 tons of screenings (an average of 2489 oz. per ton), and the net profits $1,129,047, of which $480,000 had been paid out in dividends, and over half a million held in reserve as an exploration fund. The aggregate length of driving and shaft-sinking during the year was over a mile and a quarter, the principle laid down by the directors being to open up two tons of ore for every ton taken out. Another particular in which the system of work in this mine differs from that of most of the other large mines, is that by careful handling and sorting, only very rich ore is produced, which is sacked, and the necessity of large concentrating mills to treat second-class ore (that is, ore running less than 100 oz. per ton) is obviated. I would say with regard to the Kerr Lake mine that since the close of the fiscal year several important new finds have been made, and the present rate of dividend is double that of the previous year.

One object of my visit was of a commercial nature, that is, to form an idea of the probable permanence of the camp as a whole. A power company had been formed to furnish compressed air from a central hydraulic power-plant to the mines of the entire district. Such a plant is of the utmost economic importance, because all the rocks are so hard that it is impracticable to mine without the use of machine-drills, but power is very expensive, owing to the high price of coal and the uncertainty of its supply, due to the frequent congestion of traffic on the single line of railroad that serves the district. One naturally feels doubtful about the persistence of such extremely rich ores as are found there, the mines forming an extreme type of what in the West are denominated 'specimen mines.' Moreover, it is generally admitted, even among mine-owners, that the bonanza portion of the veins almost never extends more than 200 ft. in depth. Evidently the building of a power-plant, however favorable the conditions today, would not be a desirable investment if the mines are likely to be exhausted in two or three years. The only offset to the want of persistence in depth would be the multiplicity of veins that might exist, so that with increased facilities for working it would be reasonable to expect that a constantly increasing number of productive veins would be opened.

There has appeared recently in the Journal of the Canadian Mining Institute a paper by G. R. Mickle on 'The Probable Number of Productive Veins in the Cobalt District', which bears upon just this point. The facts upon which he bases his deductions, however, were gathered prior to July 1907, and hence do not include two and a half years of the most energetic work. He estimates that in the productive area of under 10 square miles there are 2000 to 2500 veins, of which 90% are calcite veins quite barren of metallic minerals; 10% contain only occasional small amounts of metallic sulphides and a fraction of an ounce of silver per ton, and probably less than 1% are productive silver veins. This estimate was based on an examination of certain tracts, not in the most productive area, that had been reduced in area because of the want of discovery of actual mineral. He then proceeds to count the actually developed veins, distribute them among the calculated areas of the three formations, Huronian, diabase, and Keewatin, and to compare them with the long-worked European districts where somewhat similar ones are found, Annaberg and Schneeberg in Saxony. I shall not go into details of his estimates, because the comparisons will soon lose their force when the Cobalt district is systematically prospected. Thus his estimate of 66 productive veins for the Cobalt district had, he admits, been increased to 84 by July 1909, and the preponderance of those he gives for the Huronian, being 53, to 6 in the Keewatin and 7 in the diabase, might be, in part at least, due to the more vigorous prospecting in that formation, as a result of the geological deductions of the Canadian geologists. He finds that in the Annaberg district of 21 square miles, there were about 200 productive veins, or 0.6 of a vein to a claim of 40 acres; and in Schneeberg, with an area of 3.8 square miles, 150 veins were found, or 2.5 veins per claim.

In my examination of the district, what particularly impressed me, besides the exceptional richness of the ore, was the peculiar character of the rocks as a whole, and of the fissuring of these rocks. The impression received was that the phenomena were immensely old and had been produced under unusually great pressure. All the rocks are extremely dense and hard. It is not simply that they show evidence of great regional metamorphism, for metamorphosed rocks may be rather loose-textured, but they are peculiarly close-grained, and have grown to have a general resemblance to each other, so that in hand specimens the Keewatin rocks, and the intrusive diabase are scarcely to be distinguished from each other or in some cases from the Huronian graywacke. The typical

Huronian conglomerate in the vicinity of the town of Cobalt carries rather large and generally angular fragments of granite and other rocks that do not outcrop in the neighborhood, in a fine-grained matrix of more or less fragmental material, which might have been morainal, whereas what is called conglomerate in the Kerr Lake



MACDONALD VEIN; 150-FT. LEVEL; IN BEND OF NORTH DRIFT; VERY WIDE; KERR LAKE MINE.

vicinity is a band of dark, homogeneous-looking rock, like an indurated mud, in which are rounded pebbles of similar material, the whole looking like a hardened boulder till. It seems that the suggestion of a possible glacial origin for some of these rocks has already been made, but the absence of a boulder till was one of the grounds on which it was rejected. In the Kerr Lake mine this lies between the dark greenish-gray Huronian graywacke, or altered quartzite, and the underlying Keewatin, but it is difficult to find any sharp dividing line between the two formations. The true conglomerate is supposed to overlie the graywacke, but I did not find the full series present at any one place. At the Kerr Lake mine these two formations, the Keewatin and Huronian, dipping gently northward under the lake, occupy the northern half of the claim, the rest of the area being covered by diabase, which also bounds the Huronian on the north. Its relations were not ascertained, it having been found impracticable to trace the contact between diabase and Keewatin.

That the ore-bearing fissures are true rock fractures or faults of slight displacement I feel quite certain. They contain in the wider parts broken-off fragments of the adjoining country-rock, they pass continuously and without interruption from one formation into another, and in the conglomerates they cut across pebbles or matrix indifferently. Yet no gouge or slickensided surfaces could be detected, either in primary or secondary fractures, and in some cases they are continuous with cracks that resemble contraction joints in an eruptive mass. The great majority of the veins are thin cracks a fraction of an inch in width, filled with calcite; what the miner would designate as 'very tight' seams. They are generally straight and quite barren of metallic minerals for considerable distances, and may pass into a series of parallel fractures, one of which will carry ore. In the case of important ore-shoots, they then pass into remarkably well defined veins of 3 or 4 to 8 inches in width, carrying a solid mass of cobalt and nickel arsenides, more or less impregnated with native silver and with a rather subordinate amount of gangue, mostly calcite with which a little quartz is occasionally associated. At times even greater widths are attained. In such cases there generally seems to have been a structural cause for the widening, such as a crossing of one or more fractures, or some other deforming disturbance. It is difficult to determine whether these enlargements of the veins are due to the primary or secondary fracturing; for it is very evident, as Miller states, that there have been two periods of fracturing. In one instance I saw a vein carrying native silver and calcite less than an inch in width, crossing at a low angle a vein 4 to 6 inches in width filled with massive cobalt ore; but in most instances the secondary fractures are so minute as not to be distinguishable by frequent sheet form of the native silver; on one of the polished specimens I have, properly reflected light shows very distinctly the silver following minute cracks across both cobalt ore and gangue, or else following the outlines of a more or less crystalline mass of cobalt. In the one instance where I was able to observe the vein in depth, below the zone of secondary enrichment, it had identically the same characteristics as in the levels above, where instead of 10 oz. it carried several thousand ounces per ton. Indeed, the miners distinguish between pay and non-payable ore by its feel rather than by its appearance. The thin projecting sheets and points of silver give a peculiarly rough feeling that the unenriched ore does not possess; but the native silver is by no means always visible in hand specimens of rich ore. This again is well illustrated in the two polished specimens, which are from the No. 3 vein in diabase of the Kerr Lake mine; one the ordinary enriched silver which averages over 2000 oz. of silver to the ton; the other taken from the 350-ft. level only a few feet below the rich ore, which carries less than 10 oz. of silver. In this latter specimen, however, polishing has disclosed several little points of native silver scattered through the generally thin white mass of cobalt ore. The niccolite that is present is only distinguishable with a glass as faint copper-colored spots in the general white mass.

In some cases the ore passes from one fissure system to another that makes a decided angle with it, thus producing a crooked vein. A marked instance is the No. 7 vein of the Kerr Lake mine. From the shaft the rich silver vein runs due north for several hundred feet, then bends sharply to the west. There are two systems of narrow calcite veins here, one running due north, the other nearly east and west. The No. 7 vein, as it is called, has thus far been traced 700 ft. in pay, that is, in ore that runs from 2000 to 4000 oz. The west branch has been traced to the west boundary of the claim, and is apparently a continuation of the famous Crown Reserve vein, which, like the No. 7 vein, is mainly worked beneath the waters of the lake. In tracing the No. 7 vein westward, another rich vein, the Macdonald, was struck, which runs northeasterly, and near the junction the No. 7 vein attains a width of 22 in. The vicinity of the junction of these two veins has evidently been a region of unusual disturbance. The veins there vary greatly in strike, are very irregular in width, less continuous than usual, yet as a whole they are exceptionally wide and very rich in silver. The narrow calcite vein which forms the normal continuation of the No. 7 vein has been followed for several hundred feet north without developing pay-ore. At 200 ft. north of where No. 7 vein bends to the west, an exploring drift has been driven eastward on an east-west calcite vein that for over 200 ft. was a mere line in the dark homogeneous graywacke; then it began to widen, and split into several parallel cracks, which after a little merged into a 4-in. calcite vein, and then suddenly, in a short distance, devel-

No. 7 Vein (East-West) 150-ft. Level; Several Thin Parallele Veins; Kerr Lake Mine.

oped a 6-in. vein of 4000-oz. silver ore. A cross-vein running northwest, carrying silver in considerable amount, had already been cut by the exploring drift, about a hundred feet back.

The most regularly remunerative vein in the mine has been the No. 3 vein in the southeast corner of the claim. This is a north-south vein, nearly vertical, and averaging 2 to 4 inches in width. Its pay-shoot is 300 ft. long and has been followed to a depth of 350 ft., where the ore suddenly stopped. This is entirely in diabase, whereas the No. 7 vein is in Huronian graywacke. So far as developed it is remarkably straight, and there is no essential difference in character of fracturing in the diabase or the Huronian. As I have already said, I was particularly impressed with the close character of the fractures, in strong contrast with those we are accustomed to see in the Rocky Mountain region, where width is measured by more feet than these have inches. It may be that it is less close in the mines near the town of Cobalt, where the coarse conglomerates prevail and ore containing up to 50 oz. of silver is found in the wall rocks, so that mills have been built for concentrating such materials, but it is a difference rather of degree than of kind, as far as my observations went.

I could find no evidence that the silver had been introduced from below by a later accession of metal-bearing solutions, as seems to have been implied, if not explicitly stated, by those who have written on the subject, and I am inclined to believe that the second period of fracturing has served simply to furnish channels for descending silver solutions. I further believe that the reason that in the early veins the very rich ores did not extend far into the underlying Keewatin is to be found less in the fact that the Keewatin is unfavorable to the formation of fissures, than because the downward limit of secondary enrichment has been reached about at that depth. The change from rich to poor ore is certainly a remarkably abrupt one. In the No. 3 Kerr Lake mine, it occurs within 20 ft. or so, and in the No. 7 vein at the shaft it has been said that within two feet the ore dropped from 2000 to 20 oz. The depth at which this change takes place is extremely variable. There are cases in which it has occurred within a few feet of the surface, and as already stated in the No. 3 Kerr Lake vein it is at a depth of over 300 ft. That denser, more plastic rocks may have an unfavorable influence, since in them there is less likelihood of cracks that are sufficiently open to admit the descending solutions, is quite probable, but there does not seem to be any general association of this condition with the bottoming of the bonanzas. I have in mind a single case. In the north-south portion of the No. 7 Kerr Lake vein, the bonanza seemed to stop at a band of dense black indurated slate which dips northward with the other sedimentary formations, but is above the so-called Huronian conglomerate, already spoken of as resembling a tillite. In the northwestern part of the claim, however, where this slate band has not been distinctly recognized, the bonanza has already gone down 50 ft. below the horizon the slate should occupy, and has reached a depth of 190 ft., whereas at the shaft it stopped within 100 ft. of the surface. At other points observed there seemed to be no change of rock associated with the bottoming of the bonanza zone. The microscopic study of polished specimens of the same vein in and below the bonanza discloses, as the main difference, the absence in the latter of the minute cracks traversing the vein material that characterize the former, and that evidently have served as channels for the introduction of the silver.

Van Hise has stated, as a general truth, that openings in the zone of fracture of the rocky crust gradually decrease in size as depth increases, and doubtless many of you have had occasion to observe, as I have, cases where the opening of a given fissure vein decreases very perceptibly as distance from the original surface increases, and that a fissure-opening that may have a width of many feet in its upper part, if followed to sufficient depth, is found to end in a series of very small cracks whose width is to be measured in inches rather than in feet. It would seem, therefore, that the natural conclusion to be drawn from the extreme narrowness of the fissures in the Cobalt region is that they were originally formed under the pressure of a great weight of superincumbent rock or at great depth below the then existing surface; hence that the greater part of these original fissures has been eroded away, and what we see today are merely the roots of veins that once could have been measured in thousands rather than hundreds of feet. The question then is, what evidence is to be found in the geological history of the region that would justify this conclusion? Let us search and see.

The geology of the region to the north of the Great Lakes and west of Hudson Bay has not yet been worked out in detail, but its general character is assumed to be a great plateau of low relief, composed largely of pre-Cambrian rocks in which are patches of early Paleozoic beds that have escaped erosion, presumably through being enclosed in synclinal troughs, in like manner as have the Triassic beds which are found to be infolded with the crystalline schists in the Piedmont region west of Washington. The veins, as has been seen, cut through both series of pre-Cambrian rocks as well as the igneous rocks that have been intruded into them, but so far as known did not penetrate the Paleozoic sediments, and are hence assumed to be of pre-Cambrian age. From the manner in which the exposures of the two unconformable members of the latter series are distributed, it is evident that there must have been a considerable period of erosion before the Paleozoic beds were deposited over them, though there seem to be no criteria for estimating the length of that period. Since these beds were deposited, however, and the region has been again raised above the sea, it has been exposed to sub-aerial degradation continuously up to Glacial times, which in itself is a much longer period than the entire existence of the ores of Mesozoic or Tertiary age, which constitute by far the greater part of the ore deposits of the Rocky Mountain region. The evidence afforded by the peculiar character of the phenomena of secondary enrichment at Cobalt furnishes, to my mind, a still more convincing argument in favor of the assumption that the veins, both primary and secondary, are extremely old and have been exposed to degradation for an immensely long period, for secondary enrichment and degradation are processes that go on *pari passu*, and in a given region are necessarily coördinated. It seems fair to presume, then, that the erosion and wearing away by the continental glacier was only the emphasizing of a similar process that had been going on, though at a slower rate, for much longer periods of time. Secondary enrichment of ore deposits proceeds in a sort of arithmetical progress. As the vein with its enclosing rocks commences to wear away, certain of its metallic contents, rendered soluble through oxidation, are leached down and re-deposited at a lower level, which we call the zone of sulphide enrichment because the ore in that region is abnormally enriched. But this enriched zone is gradually brought nearer the surface by continued wearing away of the latter; hence increasingly richer material is carried down, and the zone of secondary enrichment is constantly increasing in richness; but the primary ore beneath this zone, which is not reached by the enriching solutions, remains constant and unchanged in the condition in which it was originally deposited. Thus there seems no limit to the amount of enrichment that may take place, provided sufficient vertical extent of original vein is provided, and enough time allowed for wearing it down to its roots.

The exceptionally rich ores are not confined at Cobalt to any single mine, or to the veins in any one formation, and the change from bonanza ore running several thousand ounces to that containing only enough to be counted on the fingers is abrupt and rapid wherever it takes place. It is a change, moreover, that can not be explained on the assumption made by the Canadian geologists, that the silver is a later addition to the contents of the veins, if by this they mean, as I presume they must, that it came from the same general deep-seated source as did the cobalt and nickel. For if such were the case, it is impossible to understand why the rising solutions should carry up their silver contents, practically without spilling any by the way, until they had nearly reached the surface, and then suddenly dump the whole load within an extent of comparatively few feet. Furthermore, it does not appear that the secondary cracks have extended below the bonanza zone. Hence the assumption of exceptionally long periods of erosion, and correspondingly great vertical extent of veins that have been eroded away seems, if the facts have been correctly interpreted, to be the only explanation that suits the case.

The chemistry of the processes of secondary enrichment that have gone on here presents some new and interesting problems, that are well worthy the attention of those geologists who have the necessary time and energy to devote to it. Hitherto we have had to do in such studies only with the sulpho-salts of the metals, but in the present case it is their combinations with arsenic and antimony that form the predominant minerals. In the present reasoning it is assumed that the chemical action of the latter would have been of the same general nature, differing only in degree from that of the former, but the actual reactions that take place are probably more complicated, and stand in need of special investigation in the laboratory. The sulphates of the metals are in general more or less soluble and are carried down in descending atmospheric waters to be reduced to sulphides in contact with large masses of unaltered sulphides. For the present it is assumed that the same is true of analogous compounds of arsenic and antimony. Precipitation takes place more readily in proportion to the relative insolubility of the sulphides. Now the silver sulphides are relatively more insoluble than cobalt, nickel, or iron sulphides, and silver, moreover, is, next to gold, the metal most readily reducible to the native state, so that it is easy to understand that it may be precipitated in the metallic state, as well as in the state of sulphide or arsenide. On the other hand in reapproaching the surface, this metallic silver may easily combine again with sulphur or arsenic, to form a sulphate or arsenate, in the presence of sulphides and arsenides of the other metals that are being oxidized, and then resume its downward course.

The safest guide in reasoning about such deposits is the study of analogous forms of ore deposits whose geology has been carefully worked out. A most instructive parallel is furnished by the deposits of Kongsberg in Norway as described by J. H. L. Vogt.[1]

[1] *Jour. f. Prak. Geol.*, Vol. VII (1899), p. 113.

These deposits occur also in pre-Cambrian rocks, intruded by both acid and basic eruptives, but the significant point of resemblance with the Cobalt deposits is that the greater proportion of their value lies in the native silver. The very rich ore is found where the veins cross the fahlbands (or brown bands) which are belts of schist impregnated with pyrite. It had long been a puzzle to geologists to understand the reason for this enrichment in the fahlbands, and to Vogt apparently belongs the credit of determining that it was because of the presence of pyrite, which he assumed had by partial decomposition given out enough sulphuretted hydrogen to precipitate the silver from its solutions as sulphide. In these mines it is not uncommon to find bunches of native silver with a core of argentite, and native silver forming a thin coating over masses of argentite or projecting out from them in wire form. Similar phenomena are found in connection with the relatively rare occurrences of proustite (the sulph-arsenide of silver). Hence he reasons that the native silver must have resulted for the most part from the reduction of the sulphide in the presence of carbonaceous matter, so-called anthracite, which also occurs. (Graphite is said to be found at Cobalt.) Some of the silver, he reasons, must have been deposited as native because it rests at times directly on galena, blende, etc. At the time Vogt wrote, the theory of secondary enrichment as it is now understood had not been developed, and it does not appear from his descriptions whether there are any secondary fractures such as would have admitted of enrichment by downward-seeping waters, but from the manner of occurrence of the ores it seems likely that this process must have been an important factor in forming these deposits, and that they might be detected if specially sought for. His assumption, as was natural at that time, was that the present distribution is that of original deposition, the only secondary action having been the reduction of the sulphide. In the Kongsberg mines native silver is still found at depths of about 500 metres, but the tenor of the ore is said to have fallen off very greatly with increasing depth. They differ from those of Cobalt in carrying no such large amounts of cobalt and nickel, and in being prevailingly sulphides, rather than arsenides and antimonides. They are the only other important mines that I know of in which the main value is in native silver, the proportion of sulphide ore being estimated by Vogt at 5 to 10%, while others have assumed it to be even less. The total production of the Kongsberg mines is estimated to have reached a value of over 137 millions of marks, while

Cobalt is producing today over 20 million ounces of silver per year, and bids fair to produce as much or even more for many years to come.

GEOLOGY AT TREADWELL MINES.

By Oscar H. Hershey.

*The Treadwell group of mines, comprising the Alaska Treadwell, Seven Hundred Foot, Alaska Mexican, and Ready Bullion, situated on Douglas island, has been studied and described by various geologists, notably by G. M. Dawson, G. F. Becker, and A. C. Spencer. The microscopic character of the ore material was described by F. D. Adams,[1] and some notes have been contributed by Charles Palache.[2] Spencer's report[3] is the latest and most complete. I have recently been engaged in a study of these mines, extending over a period of about six weeks, and have, I believe, added something to our knowledge of the conditions under which the deposits were formed. For many years, in the minds of prospectors, the Alaska Treadwell orebody has been the type par excellence of a large low-grade gold-quartz deposit; hence, specific information as to its characteristics will be of general interest to economic geologists. The management of the mines has kindly consented to the publication of this paper. I am indebted to the general superintendent, R. A. Kinzie, for information and helpful discussion.

The high mountain backbone of Douglas island is composed of altered volcanic rocks (apparently chiefly andesites) that are commonly referred to as greenstone. These are flanked on the northeast by black carbonaceous shales, light gray quartzites, and fine-grained igneous material, all striking northwest and dipping to the northeast into a broad belt of alternating graphitic slates and sheared greenstones. The latter practically disappear at a distance of several thousand feet southwest of the mines, and nearly all the rock beyond to the shore of Gastineau channel, except for intrusives, is black slate. Running through the black slate area at Treadwell there is a long band of igneous rock varying in width from 100 to 400 ft. and averaging about 200 ft., that has long been known as

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[1]*Am. Geologist,* Vol. 4, 1889, pp. 88-93.

[2]Alaska: Harriman Alaska Expedition, Vol. 4, 'Geology and Paleontology,' New York, 1904, pp. 59-66.

[3]'The Juneau Gold Belt, Alaska,' Bull. No. 287, U. S. Geol. Surv., 1909.

greenstone. Its course and dip conform to the general structure of the country and were probably controlled by the original bedding of the sedimentary rocks. Becker[4] considered it a dike of altered gabbro of later age than that of the dikes which have been converted into ore. Spencer regarded it as a lava flow of earlier age than the ore dikes. My impression is that both are correct in part. I consider it an altered gabbro that was intruded into the sedimentary rocks before the ore dikes. Near the Ready Bullion mine, where the mass is thickest and most coarsely crystallized, it has the extremely variable texture and general appearance characteristic of batholithic masses of altered gabbro. Elsewhere it is relatively fine-grained, but distinctly granular, though the augite has been largely decomposed to chlorite and epidote, and the feldspars to muscovite and calcite. As here the term 'greenstone' properly belongs only to the altered andesites of the region, I prefer to use the self-explanatory term of meta-gabbro.

During the development of the slaty cleavage of the region, the borders of the dike were converted by pressure-metamorphism into chloritic schist and slate. The band on the northeast, or hanging-wall side of the dike, rarely exceeds 10 or 15 ft. in thickness; but that on the southwest side varies from a few feet to over 200 feet. Close to the massive rocks the schist is moderately coarse-textured and clearly is derived from the meta-gabbro. Where the band on the foot-wall side is especially wide the texture becomes finer and the grain straighter, at a distance from the massive portion of the dike, until the rock is typical slate, as much so as the graphitic slate. The fact that much of the slate in the Treadwell mines is a highly altered condition of a portion of the so-called 'greenstone' has been overlooked by previous observers. The green slate is found only between the black slate and the massive meta-gabbro, and gradually changes into the latter, in one stage being a characteristic chloritic schist. The development of schistosity and slaty cleavage along the borders of the dike has destroyed, or at least greatly obscured, the usual effects of intrusive contact. Immediately adjacent to the massive portion of the dike, the schistosity is parallel to it, but at a short distance it takes on the prevailing strike and dip of the slaty cleavage of the region, which, however, are approximately parallel to the dike and to the original bedding. The ore-dikes have been intruded into the foot-wall band of chloritic slates and schists, which is proof

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[4]'Reconnaissance of the Goldfields of Southern Alaska.' Eighteenth Annual Report, U. S. Geol. Survey.

that they are younger than the meta-gabbro. G. M. Dawson[5] identified the original dike rock that has been converted into the ore of the Alaska Treadwell mine as 'granite' related genetically to the 'granites' of the Coast Range region. Becker examined the rock after more refined methods had been introduced for study of rocks, and pronounced the original dike material a sodium-syenite, although he preferred the use of the term 'sodium-diorite' or 'albite-diorite.' Spencer preferred the latter term, and as he has expressed the latest opinion on the subject, I will adopt his term, albite-diorite.

Previous observers seem to have noted evidence of one system only of albite-diorite dikes in connection with the mines, but I believe there were two periods of albite-diorite intrusion. The product of the first I will refer to as the dark diorite and of the second as the light diorite. Most of the ore has been produced by the alteration of the latter. In the Alaska Treadwell mine where the dike is widest, the least altered portion of the light diorite has a granitic texture and resembles a typical, medium-grained, light-colored granite. As we go to the southeast along the dike, through the Seven Hundred Foot into the Alaska Mexican mine, the less altered rock gradually changes to a semi-porphyritic, light-colored rock. It varies from a medium-grained to a coarse-grained rock having large distinct phenocrysts of white feldspar. It is easily observed in the Ready Bullion mine, where kernels of it are common within and on the borders of the orebodies on the lower levels. It is, however, best preserved in the large dikes that lie southwest of the ore-dikes. Many small dikes and lenticular bodies distributed through the slates between the large dikes are composed of the finer and medium-grained varieties of it. Locally, small needles of black hornblende are present, but it seems in general to have had very little hornblende or other ferro-magnesian minerals. Spencer describes the phenocrysts as albite-oligoclase, with microperthite and some pure albite in the ground-mass. The accessory minerals are apatite, zircon, titanite, magnetite, and possibly rutile. Becker thought that among the ferro-magnesian silicates, augite generally predominated over hornblende, and that biotite was an original constituent. There is very little quartz present.

In the dark diorite, ferro-magnesian minerals, probably chiefly hornblende, are quite abundant. The rock is fine to medium grained,

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[5]'Notes on the Ore Deposits of the Treadwell Mines, Alaska.' Read before the Royal Society of Canada, May 8, 1889.

and never porphyritic. Chlorite and epidote have been largely developed, giving much of it a distinct greenish tint. Indeed, in places in the mine workings it has been classed as greenstone. It is commonly mineralized, but usually not enough to constitute ore. Its area abounds in irregular, branching, dike-like bodies of light-colored ore, suggesting that it has been intruded by the light diorite; but for a time it was a question in my mind whether these light-colored streaks did not represent portions of the dark diorite that had been modified by vein-like action to resemble the ore of the light diorite. This led to the further suggestion that the two kinds of diorite represent the same intrusion, the differences noted being due to local variation in the conditions of solidification. However, much of the dark diorite seems to have become schistose before the intrusion of the light diorite. They probably bear a relation to each other similar to that between the several varieties of diorite that compose any large batholith of diorite in the Coast Range region, and the time interval between their intrusions may have been a short one. The dark diorite occurring in the mines was intruded in two elongated masses at or near the contact between the black slate and chloritic slate. The larger body was about 1000 ft. long, but I do not know how wide, because it has been rent by the light diorite. Important remnants of it occur as a medium-grained gray crystalline in the southwestern part of the Alaska Treadwell mine, from the surface to the lower levels. The other mass of dark diorite is in the Alaska Mexican mine and has a length of 1100 ft., and a maximum width of 130 ft. Dark diorite also enters largely into the composition of two other large albite-diorite masses lying to the southwest of the mines. A system of light albite-diorite dikes was next intruded, chiefly along two lines, of which one was mainly in or at the contact with the chloritic slate band on the foot-wall side of the meta-gabbro dike, and the other in the black slate. In the immediate vicinity of the mines, the massive meta-gabbro acted as a hanging-wall limit to the intrusion, so that while there are hundreds of small dikes and lenticular bodies in the slates on the southwest of the meta-gabbro, there are none northeast of it.

Within an area of 2.6 miles long and 0.8 wide which I mapped, albite-diorite occurs in six principal masses. They are too wide relative to their length to be typical dikes, and too much elongated to be termed batholiths, but I will continue to use the term dike. The Starr dike has a known length of 5000 ft., a maximum width of outcrop of 1100 ft., and an average width of outcrop of 330 ft. However, as it outcrops on the summit and steep northeast slope of two high hills, its actual width is much less than the width of outcrop. Where the outcrop is 1100 ft. wide, the dike is probably 900 ft. wide; it is the widest body of albite-diorite in the vicinity of Treadwell. Both the dark and light diorite enter into its composition, the latter greatly predominating.

The Bear's Nest dike has a length of 3300 ft., a maximum width of outcrop of 600, and an average width of outcrop of 260, though its true width is much less. Both kinds of diorite enter into its composition. The Starr and Bear's Nest dikes and two others back of Douglas City constitute the southwest line of large dikes; this is in the black-slate area. The Treadwell Mexican dike includes all the orebodies of the Alaska Treadwell, Seven Hundred Foot, and Alaska Mexican mines, except a small one near the southeast end of the last mine. At the surface it has a known length of 3800 ft., a maximum width of 400 ft., and an average width of 85 ft. It consists of three enlarged parts, separated by long, narrow portions. The most northwesterly enlargement is divided by long overlapping tongues of chloritic slate into the so-called 'South vein' and 'North vein.' The first was intruded into the dark diorite, mainly in a body about 600 ft. long and 300 ft. in maximum width. Small arms of the light diorite have intruded into the dark diorite, so that little of it is entirely free from them. Where these arms are numerous they have carried enough gold into the rock to constitute profitable ore. There are also a few places where the dark diorite itself is sufficiently mineralized to be ore, but generally the area of the dark diorite on each level is not stoped. Near the surface practically all of the light diorite is ore. The remainder of the great northwestern enlargement is about 1800 ft. long and 150 ft. in maximum width, of which nearly all, near the surface, has been removed in the Glory Hole and Seven Hundred Foot pit, except a considerable body at the extreme northwestern end which was found of too low a grade. This portion of the dike has been intruded entirely in the band of chloritic slate and schist which was developed on the southwest side of the meta-gabbro dike, and the isolated horses and projecting splinters are of chloritic slate, except that a little massive meta-gabbro appears in a few horses near the hanging wall on the 110-ft. level. The larger structural features of the northwestern enlargement are remarkably persistent down to the 1450-ft. level, the deepest fully-developed level in the Alaska Treadwell mine. The chloritic slate horses vary a little in size and position, and in the South vein the relative proportions between the dark and light diorite vary considerably from level to level, but the general structural relations remain unchanged, and the size of the enlargement, as a whole, does not greatly differ. Next, there is at the surface an interval of 1000 ft. which is known from underground work to be practically a continuous 'pinch.' However, it becomes shorter with depth and finally changes into a body of workable ore which is separated from the adjacent swells by short pinches. At the most northwesterly Alaska Mexican pit, there was an enlargement probably 200 ft. long and 50 ft. in maximum width, most of which, near the surface, was removed in the pit. It enlarges with depth into what may be called the main Mexican swell, which, on the 1100-ft. level is over 700 ft. long and has a maximum width of 100 ft. Near the surface, after another pinch, about 400 ft. in length, the dike opens into the eastern Mexican swell, which was principally mined in two surface pits and was found to be 500 ft. long and probably 75 ft. in maximum width. This swell was due to the erratic behavior, near the surface, of a mass of dark diorite into which it was partly intruded, and it has not been found below the 330-ft. level. Near the southeastern end of the Alaska Mexican mine there is a sharp bend to the east in the meta-gabbro dike. The slaty cleavage bends also, but not so much as the dike, and since the ore follows the slaty cleavage, it is carried off into the black slates, and the eastern swell is almost entirely separated from the chloritic slate. Back of the eastern swell there is a smaller ore-bearing dike in the black slate. These are the only places in the mine where commercial ore occurs in dikes having black slate on both walls. The Ready Bullion dike at its outcrop had a length of 560 ft., a maximum width of 60 ft., and average width of 40 ft. With depth it shows a remarkable increase in width accompanied by a slight decrease in length, so that it is practically a large triangular pipe rather than a dike. On the 1350-ft. level it is probably 500 ft. long and 290 ft. in maximum width. It comes to a rather sharp point at the southeast, but terminates northwesterly by fingering out in the chloritic slate. Its position and pitch are evidently controlled by a wedge of chloritic slate into which it has been intruded. This wedge, which is a few feet wide at one end and over 200 ft. wide on the lower levels, at the other end, may be related to an abnormal swell in the meta-gabbro dike a short distance southeast of the mine.

If the two large southerly dikes be considered as one line of dike and the ore-dikes in the mines as another, the swells in one line will be found opposite the pinches and intervals in the other line. There is a very simple explanation of this. These albite-diorite dikes did not make their way up through the strata by 'overhand stoping,' as it is supposed that many granitic batholiths have, nor did they rise freely in open fissures as many ordinary dikes have. The melted rock forced its way up through the slates under great pressure, rending them and wedging them apart. In minor detail, the contacts are splintery, and tongues of slate project far into the dikes; but looked at from a broader standpoint, the slates are found to curve around the swells in the dikes. Nearly everywhere the strike and dip of the slates are approximately parallel to the borders of the dikes. The albite-diorite had to raise the slates above it, but there was a limit to the distance to which it could force them. The larger dikes divided this space between them. Thus when one dike appropriated practically the entire space available, there was opposite it a pinch or interval in the other line of dikes. This idea has a practical bearing on the search for ore in virgin ground. In the belt of black slate between the Alaska Treadwell swell and the Bear's Nest dike there is a long band, generally 25 or 30 ft. wide at the surface, of white to dull-buff rock that resembles a quartzite of heavy-bedded structure and conforms strictly to the slaty cleavage. However, at two places there are traces of feldspar crystals in it, and in the absence of a petrographical investigation I consider it probably an aplite dike. A short distance south of the Seven Hundred Foot pit there is a small lenticular area of a greenish, rather coarse-grained, massive crystalline rock of the mineralogical composition of diorite, but with the general appearance characteristic of meta-gabbros. It has a fresher appearance than the meta-gabbro on the northeastern sides of the mines, and contains many small inclusions of porphyritic albite-diorite like that of the small dikes so abundant in its vicinity. I have never seen any albite-diorite inclusions in the meta-gabbro dike on the hanging-wall side of the mine, though Spencer states that Becker found one in it. Perhaps it came from this other, and presumably younger, meta-gabbro.

At various places in the Alaska Treadwell, Seven Hundred Foot, and Alaska Mexican mines there are basalt dikes that vary from a fraction of an inch to 4 ft. in thickness, 6 and 8 in. being a common thickness. They have a general course near north-south, and stand vertical or dip steeply toward the west, or, less often, toward the east. A minette dike 2 to 3 ft. thick has been cut on the Alaska Mexican 1100-ft. level. Becker was inclined to see a genetic connection between the largest basalt dike (the only one then known) and the ore, but I agree with Spencer that the basalt dikes are younger than the ore and have nothing to do with its origin. Not all of the Treadwell Mexican and Ready Bullion dikes is commercial ore. The causes that have controlled the position and shape of the ore-shoots within the dikes and their variation from level to level are obscure, but I make here a few suggestions. Spencer, in the report cited above, has given a very minute description of the ore and discussed its origin at length; the necessarily limited nature of this paper will not permit of a similar treatment of the subject. Briefly stated, the ore consists of two parts, one of which is dike rock in which secondary albite has been developed (largely by replacing the interstitial microperthite, though some was deposited by vein-waters from material added), and which is impregnated with calcite and pyrite, only a little silica penetrating where there were no open fissures. The dike was in part shattered and then filled by reticulating veinlets of calcite and quartz, which also carry sulphides. Becker thinks the disseminated pyrite has probably been derived by the action of sulphydric acid on the ferromagnesian minerals and that the bunched pyrite which is accompanied by much calcite has entered the rock in a state of solution. The secondary minerals, as determined by Spencer, are albite, uralite, green mica, epidote, chlorite, zoisite, calcite, quartz, sericite, rutile, pyrite, pyrrhotite, with molybdenite, galena, sphalerite, chalcopyrite, and arsenopyrite occurring exceptionally. Some of the magnetite may also be secondary. There is probably some siderite also. The quartz and calcite veinlets, which constitute nearly one-fifth of the mass of the ore, occur chiefly in two sets of fractures, one of which is approximately parallel to the structure of the enclosing slates and in places prolongs the veins beyond the ends of the dikes as narrow quartz-veins which are said to exceed the average tenor of the ore, but are too small to mine. The most prominent system dips toward the foot-wall. In general, the best ore is that which contains the greatest number of quartz and calcite veinlets, though there are places where good ore has been formed without them, and other places where rock abounding in veinlets lacks the usual quantity of pyrite and is too low in grade to work; for the gold is apparently mainly associated with pyrite, though there are a few places where rock well supplied with pyrite yields only a very small amount of gold. The gold is generally very fine, but some has been seen in coarsely crystalline calcite, and

Adams observed some mechanically enclosed in crystals of pyrite. Spencer thinks the 60 to 75% that is recovered by amalgamation may be partly in the non-metallic minerals, though the non-amalgamating portion undoubtedly occurs with the pyrite. The concentrate, chiefly pyrite, with some pyrrhotite and magnetite, averages 2% of the ore. The pyrite in places extends several feet into the slate walls and horses, but such material generally is of very low grade, though some of it is mined and known as 'brown ore.' It is evident that the formation of the ore was dependent on the fracturing of the dike. This was the result of pressure originating beyond the dike. The so-called ore-shoots consist of those portions of the dike that yielded most readily to the compressive stress, became most permeable, and hence were most strongly acted on by the vein-forming waters. The distribution of the gold is very irregular. During the progress of development samples are taken at every round. They yield by assay at the rate of from a trace to over $20 per ton. Upon being averaged for certain sections of drifts they vary from less than $1 to over $10 per ton. In the following table, No. 1 represents 210 ft. of a drift on the 1450-ft. level of the Alaska Treadwell mine; No. 2, 160 ft. on the 1210-ft. level of the Alaska Mexican mine; and No. 3, 150 ft. on the 1350-ft. level of the Ready Bullion mine. They were selected at random and are given to show how the gold content varies rapidly in short distances within the orebodies. The figures may interest the prospector who has a large low-grade mass of gold ore with a few assays to indicate value.

By studying the averaged assays, one can get a very clear conception of the total gold content of the dikes on the different levels. There is a peculiar horizontal banding in the gold content of the dikes in all the mines. Thus in the Ready Bullion mine there appears to have been a rather steady decrease in the gold content from the surface to the 600-ft. level; from there, an increase to the 1350-ft. level, below which the pendulum has swung temporarily in the other direction. This variation is not directly related to the maximum thickness or size of cross section of the dike; but, of course, it influences the size of the ore-shoot on different levels; for, where the total gold content is low, a relatively small amount of the dike is commercial ore, and on such a level as the 1350-ft., where the total gold content is the highest in the mine, nearly all of the dike is workable ore. I have been unable to determine that the ore-shoot is closely connected with any structural feature. It seems to wander about in the dike. The only point it never misses is the foot-wall side a little southeast of the centre; the part of the dike it most avoids is the extreme northwest. In the South vein of the Alaska Treadwell mine, the gold content was relatively high from the surface to the 220-ft. level; thence decreased to the 440-ft.

No. 1.	No. 2.	No. 3.
$4.55	$0.65	$7.73
0.41	3.51	6.70
2.68	11.98	3.10
8.27	9.71	2.30
3.51	12.81	3.87
1.86	6.20	4.13
2.48	3.30	13.00
1.65	6.60	7.23
1.65	1.23	18.00
1.03	2.27	12.00
1.65	1.65	10.34
4.96	2.89	7.23
0.62	3.72	8.20
0.41	0.45	5.68
1.65	1.23	4.64
3.51	1.03	1.27
1.03	Trace	1.54
2.89	2.68	7.23
4.14	0.41	6.70
1.44	5.37	3.60
0.41	Trace	5.68
1.03	0.82	1.54
1.23	0.62	3.10
5.78	0.82	5.18
4.96	0.82	1.27
0.62	6.20	7.73
3.72	5.99	
4.55	2.07	Average.. $6.11
2.07	11.57	
0.82		
3.72	Average.. $3.67	
3.30		
0.82		
4.14		
3.72		
2.07		
0.82		
1.03		
Average.. $2.50		

level, thence increased irregularly to the 1450-ft. level, the present lowest fully-developed level and by far the best in the mine. This variation seems to have been more or less directly related to the variability of maximum thickness of the light diorite, the highest average gold content being found on those levels having the widest body of light diorite. The South vein contains one large ore-shoot which, where the body of light diorite is very wide, occupies nearly the whole of it, but where the light diorite is narrow, it is inclined to wander about a bit. However, as it cannot get out of the light diorite body, it must have the same general pitch. In the North vein, the gold content seems to have been rather high, down to the 220-ft. level. Thence it decreased to the 330-ft. level, after which there was no great change to the 750-ft. level. But the 900-ft. level was so poor that very little of it was ore, although the South vein on this level was good. The North vein quickly picked up again below the 900-ft. level, and on the 1050-ft. level its average assays are better than those of the South vein. Thence to the 1450-ft. level, the North vein maintains a good gold content. The principal shoot of ore in this vein is related to the widest part of this portion of the dike. It varies greatly in length, width, and value, but is absent from only one level. 'There is a considerable body of worthless rock at the northwest end of the North vein on all levels but one. Its notable feature is that while it has considerable quartz and calcite in veinlets, it is relatively low in pyrite.

In the Alaska Mexican mine, the levels are driven largely along or in the foot-wall, and the average assays are not a good indication of the total gold content. It is known, however, that the portion between the 880 and 990-ft. levels is, so far as ore is concerned, the best part of the mine. Near the surface the main swell in the dike is relatively small, but largely ore down to the 440-ft. level. Thence to the 660-ft. level the main swell is very wide, and the ore-shoot tends to hug the foot-wall side of the northwestern half. Near the 770-ft. level it lengthens so as to extend almost the entire length of the swell. It varies greatly in width, and in some places is confined under a horse. Below the 990-ft. level the ore-shoot contracts and tends to draw to the northwestern part of the swell as it did above the 770-ft. level. The eastern swell is largely ore though I believe it is most extensively stoped in the southeastern half. Below the 330-ft. level, a new swell appears under a part which at the surface is a long pinch, and at the 1100-ft. level it has reached a maximum width of 75 ft. Nearly all of it is ore on all levels on which it is wide enough to stope. It is separated from the big northwestern swell on one side, and the main Mexican swell on the other side, by very short pinches. Indeed, on the Alaska Mexican 990-ft. level and Alaska Treadwell 1050-ft. level, there is a practically continuous ore-shoot from end to end of the developed portions of the dike, a distance of 2500 ft. though it does not everywhere include all of the width of the dike.

In short, the evidence is too conflicting to warrant the statement that the ore-shooots are closely controlled by the structure of the dikes except that, of course, commercial ore is confined to the swells and pitches with them. Becker suggested that the pressure that crushed the dikes was applied in a nearly horizontal direction, but Spencer thought it likely that the movement was nearly vertical. He regarded the fractures as produced during general continental uplift which involved expansion rather than shortening. A horizontal pressure exerted unequally in different zones might explain the banding of the gold content and the amount of ore on different levels. I have no very strong conviction as to the direction of movement. To my mind the dikes have behaved like heterogeneous bodies of rock that would, naturally, yield unequally to pressure. It may be that that is partly the secret of the apparently unsystematic distribution of the severely crushed areas. On account of its physical character, the dark diorite was not as generally crushed and converted into ore as the light diorite; the latter also may have varied in texture and composition in a manner common to granitic and dioritic masses in general. Certain seams are sometimes pointed out as limiting ore, but they appear to me to be post-mineral fractures, and their presence in places on the borders of orebodies is perhaps due, not to their having limited the formation of the ore, but to the physical condition of the rock on the borders of the orebodies having been favorable to their development there.

As to the nature of the waters to which the formation of the Treadwell ores is assigned, Spencer argues, from the character of the metasomatic replacement accomplished by them, that they were heated ascending waters of magmatic origin emanating from rock masses far deeper than those in which the mineral deposits are found. He says that "such a reservoir of molten rock as is here assumed, would be an adequate source of water and of all the chemical elements which are found in the ore deposits." G. M. Dawson thought it more probable that "the water included in the adjacent sedimentary deposits became vaporized by the heat of the intrusive mass and found its way to the surface in the form of steam through the substance of that mass." I am inclined to accept the magmatic theory, but I am not certain that the gold was derived from the magma that may have supplied the water. Dawson thought that the slaty argillites at depth may have furnished both the gold and the pyrite. My difficulty arises from the following facts: All the larger albite-diorite dikes, and many of the smaller ones, in the vicinity of Treadwell were more or less subjected to mineralizing action. Those along the chloritic slate band on the foot-wall side of the meta-gabbro dike were in large part converted into commercial ore; those in the black slate at a distance from the chloritic slate practically never were. The Starr and Bear's Nest dikes contain a little disseminated pyrite throughout, though the larger portions of them are not notably mineralized. Here and there, however, are portions that have been converted by vein action into material resembling the ore in the mines, but they seem nowhere to carry commercial ore. Assays run generally from 20 to 60c. per ton, and rarely reach $1. They have not the amount of gold that goes with other similar material in the dikes along the chloritic slate belt. If the solutions derived their gold from the dioritic magma that supplied the water and were not influenced by the wall-rocks of the dikes, they must have deposited as much gold in connection with a certain amount of quartz and calcite veining and pyrite impregnation in one set as in the other. I doubt that the slate walls have had an important influence over the deposition of gold in the broad dikes. At any rate, I would expect the carbon of the black slates to have had a stronger influence than any mineral in the chloritic slates. Another explanation is possible. The gold may have originally been present in an extremely disseminated condition in the meta-gabbro dike, part of which later was converted into chloritic schist and slate. Much of the latter at great depth became incorporated in the albite-diorite that was intruded in or along the border of the band. The vein-forming waters may have dissolved the gold from the chloritic slate and deposited it higher in the crushed portion of the albite-diorite dikes. The dikes in the black slate may have had a much poorer source of gold. This hypothesis is weak, in that it seems improbable that the amount of chloritic slate involved could have yielded sufficient gold to supply the many millions of dollars' worth of it in the ore-dikes.

Perhaps the calcite present in the ore-dikes has had an influence on the deposition of the gold. Becker thought the calcite was hardly derived from the decomposition of the plagioclases of the albite-diorite, as there was not enough of the anorthite molecule present. It seems that the black slates are, as a whole, rather calcareous, and occasionally contain thin beds of black limestone. The greenstone schists are composed largely of chlorite and calcite. But the most probable source of most of the calcite in the ore-dikes is the meta-gabbro of the hanging wall and its modified form, the chloritic slate and schist. Becker says calcite is more abundant in the meta-gabbro than in the diorite. That in the chloritic slate band which became included in the albite-diorite at great depth was probably dissolved and re-deposited higher in the ore dikes. In that case, the dikes along the chloritic slate band should be richer in calcite than those at a distance in the black slate, but I am unable to state from observations that they are. I offer the preceding speculations merely as suggestions, as I am not certain as to the cause of the marked difference in gold content of the two sets of dikes, though I am satisfied that it is in some manner related to the fact that one is in or near the chloritic slate and the other wholly in black slate.

Dawson expressed the opinion that the ore-dike of the Alaska Treadwell mine represents the upper portion or feather edge of a granitic intrusion, and that in depth the ore mass would be found to pass gradually into ordinary unaltered granite. Development has shown, however, that there is not a great increase in thickness of the dike and gradual decrease in average gold content with depth. Although the dike material must have expended energy as it arose and had less power to rend the slates, this may have been largely or wholly offset by the fact that as height was attained there was less slate to lift. There seems to have been a rather even balancing of these opposing conditions within the vertical range of the present mines. (If the slates subsided on the magma, the physical effect was the same so far as the dikes were concerned.) I expect the larger albite-diorite masses, including the Treadwell Mexican, to become less dike-like in depth and more like the small batholiths that are commonly found in the vicinity of the great granitic and dioritic masses of the Pacific Coast region from Alaska to southern California. Of course, there must be a point below which the Treadwell-Mexican batholith made its way by overhand stoping rather than by merely forcing the slates apart, and below that point it probably widens into a great body that may be part of the Coast Range dioritic *massif*. The crushing and mineralization are probably dissipated within this enlarged part of the batholith, as suggested by Dawson.

I have recently become interested in the question of whether there is, in the majority of large gold-quartz veins throughout the world, a gradual decrease in the gold content of the primary sulphide ore with depth.[6] If such a rule exists, the Treadwell group

[6]*Mining and Scientific Press*, July 16, 1910, p. 85.

of mines is a conspicuous exception to it. The annual statements of the company show that the total yield per ton of the Alaska Treadwell mine was \$3.79 during the first five years up to May 1890; declined to \$1.88 in 1900-01; averaged \$2.20 from June 1902 to May 1909, and was \$2.79 for the year ended May 31, 1910, with a general average of \$2.43. For the Alaska Mexican mine, it was \$2.79 in 1894; reached a minimum of \$1.89 in 1900; rose to \$2.92 in year ended December 15, 1903; reached \$3.03 in year ended December 15, 1906, and \$3.97 in year ended December 15, 1909, with a general average of \$2.68. For the Seven Hundred Foot mine it was \$1.72 in 1899; \$1.50 in 1901; and \$2.41 for year ended December 15, 1909; with a general average of \$1.94. For the Ready Bullion mine, it averaged \$2.57 for 1898 and 1899; reached a minimum of \$1.48 in year ended December 15, 1902; and rose to \$2.17 for year ended December 15, 1909, with a general average of \$1.94. The marked decrease in the value of the ore milled in the early history of the Alaska Treadwell mine was the result of increasing the tonnage by mining low-grade rock. Doubtless some of the decline in value, and probably nearly all of the recent increase in all the mines, has been the result of advancing the mines down through the alternating bands of high gold content and low gold content, brought out in this paper. Spencer expressed the opinion in 1906 that it was impossible to make out any progressive change in the character of the ore as depth was attained, and that the assay charts showed the ore in the lowest levels to be quite as good as in the upper workings. Since that date, all the mines have penetrated the better levels. The best level in the Alaska Treadwell mine is 1300 ft. below sea-level; in the Alaska Mexican mine, 900 ft. below sea-level; and in the Ready Bullion mine, 1000 ft. below sea-level. The general superintendent also expresses the opinion that there has been no general impoverishment of the dikes in depth. The assay-charts that I have studied fully support his view. The thick oxidized zone once present near the surface of the dikes was removed by glacial action, and only a very shallow zone formed since the disappearance of the ice. As Spencer says, "there has been no important secondary concentration of value by oxidizing-waters near the surface." Practically all the ore belongs to the zone of primary sulphides. There can be little doubt that such ore as has been mined from the surface to the lowest levels of the mines will continue to a much greater depth.

THE SADDLE-REEF.

By T. A. Rickard.

This type of ore deposit bears the local name originating at Bendigo, in Australia, where it was first exploited and is best exemplified. It is a fact, however, that from 1854, when the quartz lodes were first mined at Bendigo, up to 1888, when E. J. Dunn published a note in one of the quarterly reports of the Mining Department of Victoria, the real structure of these bodies of gold-bearing ore was not recognized. Moreover, the fact that Mr. Dunn had furnished a key to the economic geology of the district was not generally known when I first went to Bendigo in 1890, nor did I see his explanation until the nature of the lodes had been ascertained by myself[1] from the examination of the geological evidence obtained in the mines. This led to a personal controversy long ago happily ended;[2] it is worth mentioning now, in the first place, in order to record Mr. Dunn's priority of scientific discovery; secondly, to emphasize the fact that two investigators separately came to the same conclusion; and, thirdly, that for 35 years the superintendents of the Bendigo mines directed the work of exploration underground without the one clue that they most needed. For whatever may be the theory concerning the origin of these ore deposits—and as to that my friend Philip Argall and I broke several lances years ago[3]—it is certain that no goldfield so well illustrates the structural relations of ore deposits, a phrase the wording of which recalls one of the most valuable contributions ever offered by the geologist to the miner.[4] Thus, in preparing a brief account of the saddle-reef, I find

[1]'The Bendigo Goldfield,' by T. A. Rickard. *Trans.* Amer. Inst. Min. Eng., Vol. XX, pp. 463-545.

[2]*Trans.* Amer. Inst. Min. Eng., Vol. XX, p. 772. Also Vol. XXI, pp. 712-713.

[3]'The Origin of the Gold-bearing Quartz of the Bendigo Reefs, Australia'; by T. A. Rickard. *Trans.* Amer. Inst. Min. Eng., Vol. XXII, pp. 289-321. Discussion by Philip Argall; *Ibid*, pp. 740-763. Reply by Rickard; *Ibid*, pp. 763-774. Discussion by Argall; *Trans.* Amer. Inst. Min. Eng., Vol. XXIV, pp. 933-939. Reply by Rickard; *Ibid*, pp. 939-940.

[4]'The Structural Relations of Ore Deposits,' by S. F. Emmons. *Trans.* Amer. Inst. Min. Eng., Vol. XVI, pp. 804-839.

myself turning to the notes, papers, and discussions of twenty years ago; and with pleasure, because the retrospect enables me to realize that the little whirlpools of controversy have become quiet, while the main stream of general knowledge has advanced steadily.

The country at Bendigo consists of alternating beds of slate and sandstone of Lower Silurian age, as proved by the fossils of *graptolites*. The sedimentary rocks have been squeezed into sharp flex-

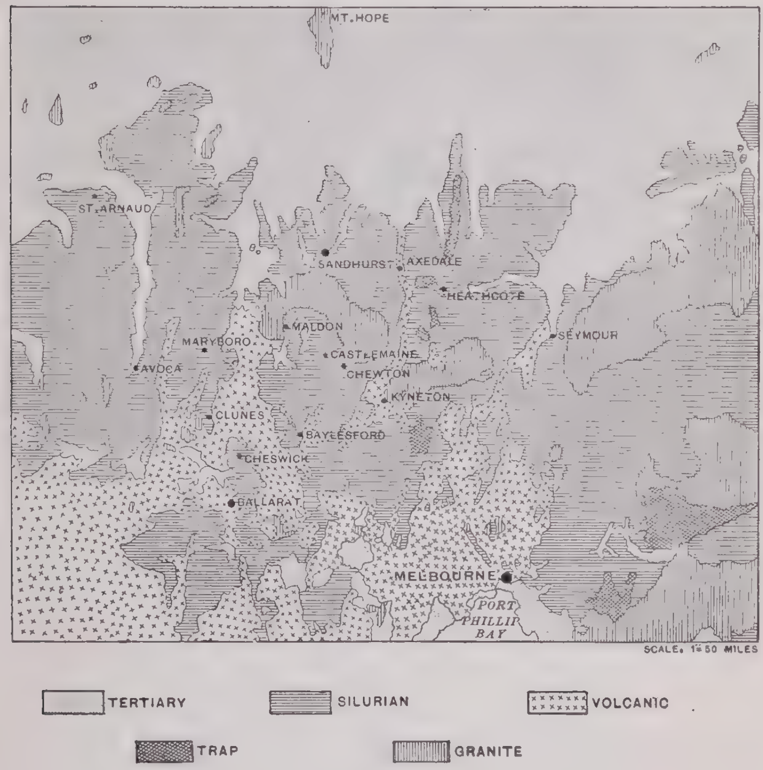


FIG. 1.

ures by regional movements associated with the irruption of granite, which constitutes the ridge of Mt. Alexander, south of the goldfield, and protrudes elsewhere in isolated masses, such as Mt. Hope. The general geology of the region is indicated by the accompanying map, copied from the 'Geological and Physical Geography of Victoria', by R. A. F. Murray. It will be noted that the old name 'Sandhurst' appears instead of 'Bendigo'. Originally named 'Bendigo' in 1851, the goldfield was early re-christened 'Sandhurst,' after the British

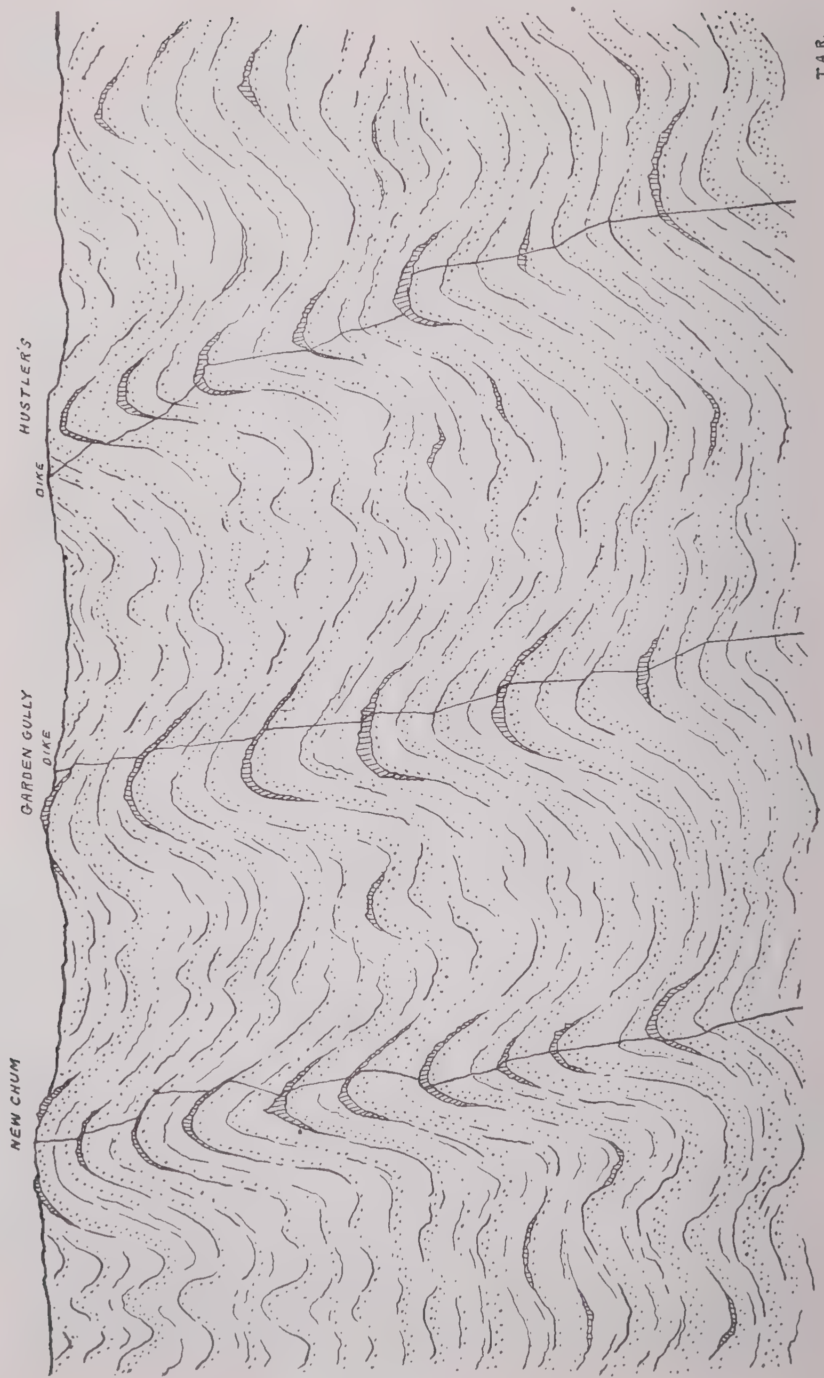


Fig. 2. Ideal Section of the Bendigo Goldfield, Showing the Three Main Lodes.

military depôt, but the old name was restored in 1890, and in that second baptism I played a minor part.

The term 'saddle-reef' is open to objection, like most local terms, but it became established before the economic geologist had an opportunity to substitute a word technically more correct. The 'saddle' is an anticline-lode; the gold-bearing quartz conforms to the crests of folds in highly contorted strata of slate and sandstone. The lodes coincide with anticlinal axes having a northerly strike and an easterly dip. Each lode, or 'line of reef', consists of a series of 'saddles', or anticlinal formations of quartz, which succeed each other at varying intervals of depth. (See Fig. 2.) Looking north, the right and left parts of the saddle are termed the east and west 'legs', while the apex is called the 'cap'. The rock in the axial portion of a fold is called 'centre country'. Owing to the deposition of quartz along bedding-planes and cross-fractures, it is not unusual to find small bodies of quartz that have a slight resemblance to saddles; these are known locally as 'false' saddles. They have no economic importance. (See Fig. 3.) As the general dip of the principal anticlinal axes is eastward, the miners say that "centre country dips east." Thus a vertical shaft sunk on the eastern side of a 'line of reef' will cut through the east legs of successive saddles, then penetrate centre country, and if continued downward it will intersect the west legs before reaching the synclinal country or the confused bedding that separates the main 'lines of reef'. If the shaft be continued still deeper, it will cut into the east legs of the next series westward, and repeat the successive variation. For example, at 560 ft. a cross-cut finds centre country at 65 ft. west of the shaft, while at 2500 ft. it is 70 ft. east of the shaft; thus in 1940 ft. of vertical descent the anticlinal axis has dipped so as to be 135 ft. farther east. In this way the miner is impressed with the fact that the general dip is eastward.

It is easy to get the idea of a saddle as seen in section, but we must grasp the idea also that it has extension in strike. I remember standing in the stope made by the removal of the saddle at the 980-ft. level in the Johnson's mine. It was a huge vaulted chamber; overhead the curve of the saddle had left a well defined arch, and the foot-wall on which I stood looked like the top of a boiler. I walked along the crest of this curving foot-wall of a fine saddle-reef and noticed that it sloped. That marked the pitch of the formation. This pitch varies so that taking a length of several miles the longitudinal section gives an undulating line, to which

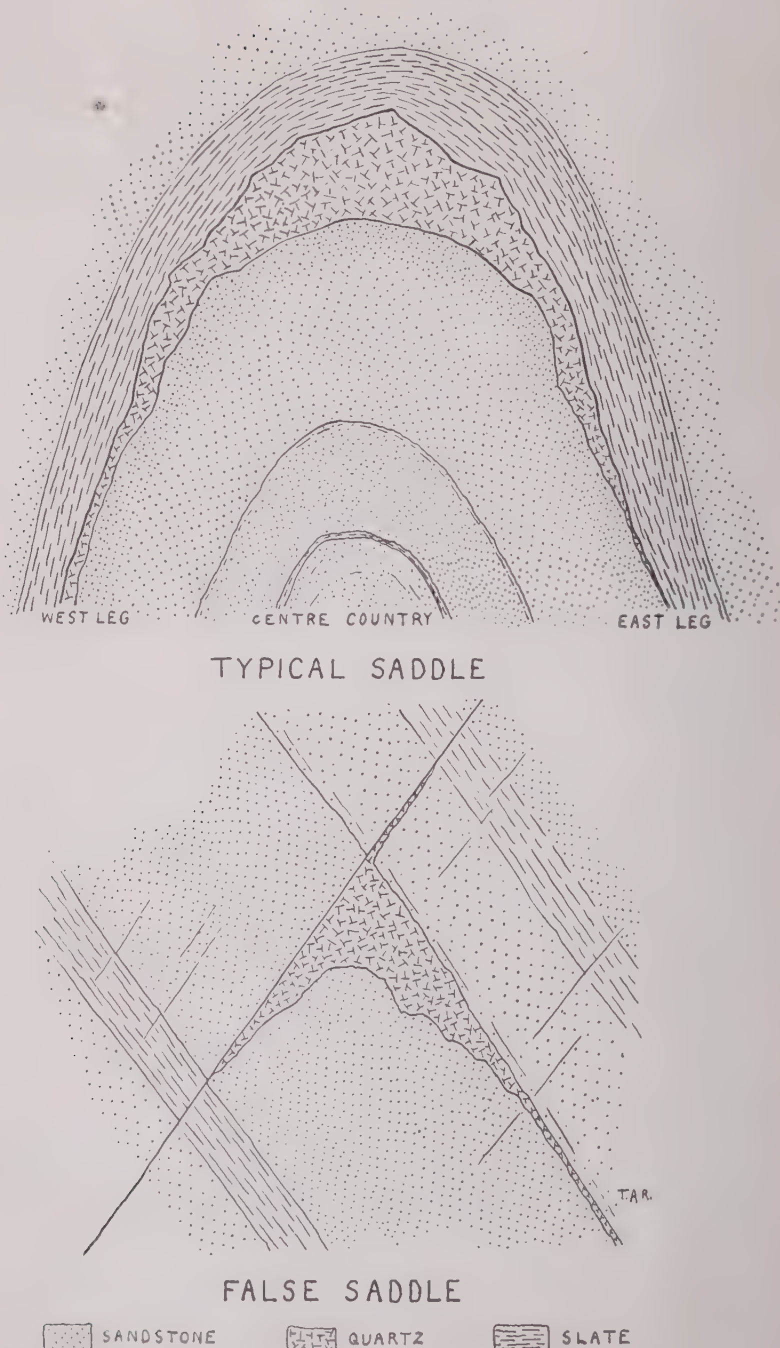

WEST LEG
CENTRE COUNTRY
EAST LEG
TYPICAL SADDLE
T.A.R.
FALSE SADDLE
SANDSTONE
QUARTZ
SLATE

Fig. 3.

the successive saddles conform. Thus, when viewed in cross-section, the saddles are like a series of bows on an arrow of indefinite length, the arrow marking the anticlinal axes; again, the saddles resemble arches varying in curve from the rounded Norman to the pointed Gothic, according as the country-rock has been bent in folds gentle or acute. Regarded lengthwise the saddles are like Roman bridges of indefinite width or pent-houses of exceeding length, overlapping each other and separated by intervening beds of slate and sandstone. In perspective the saddle-reef may be likened to the roof of a thatched cottage, the ridge undulating and the thatch varying in thickness. Viewed from any standpoint the saddle-reef is a beautiful example of geological structure.

The upper workings of the South New Chum mine (Fig. 4) offered a simple illustration of the prevailing lode-structure. The two legs (*A B* and *C D*) of a truncated saddle-reef outcropped at a distance of 120 ft. south of the shaft. At a depth of 125 ft. the shaft cut through the cap of another 'formation', the legs of which were found by the cross-cut on the 170-ft. level at points 10 ft. east and 34 ft. west, respectively, from the shaft. These same 'legs' were found on the 280-ft. level, at points 74 ft. east and 84 ft. west, respectively, from the shaft; and at this same level a third saddle was cut. All three 'formations' pitched southward, as shown in the longitudinal section. When I first went underground at the New Chum & Victoria mine, in April 1890, it was explained to me that "the east leg goes with the formation but the west leg cuts across it." So it seems at first glance, particularly in the central part of the goldfield. The cleavage obscures the stratification. Although the mine managers were so long misled by the deceptive harmony between the cleavage and the bedding of the rock on the east side of the saddle, and equally deceived by the complete obliteration of the bedding on the west side, they nevertheless exploited these ore deposits on the assumption that they were arched bodies of quartz occurring in sequence downward. Even to one not in possession of the clue to the true structure of these lodes it should seem strange, if the quartz follows the country-rock on one side and transgresses it on the other, that the east and west legs show so little difference in behavior. And it cannot be doubted that if the underground exploration of the saddle-reefs had been guided by correct theory, the early development of the goldfield would have been expedited in many ways.

The vicissitudes of mining in such a locality can easily be imag-

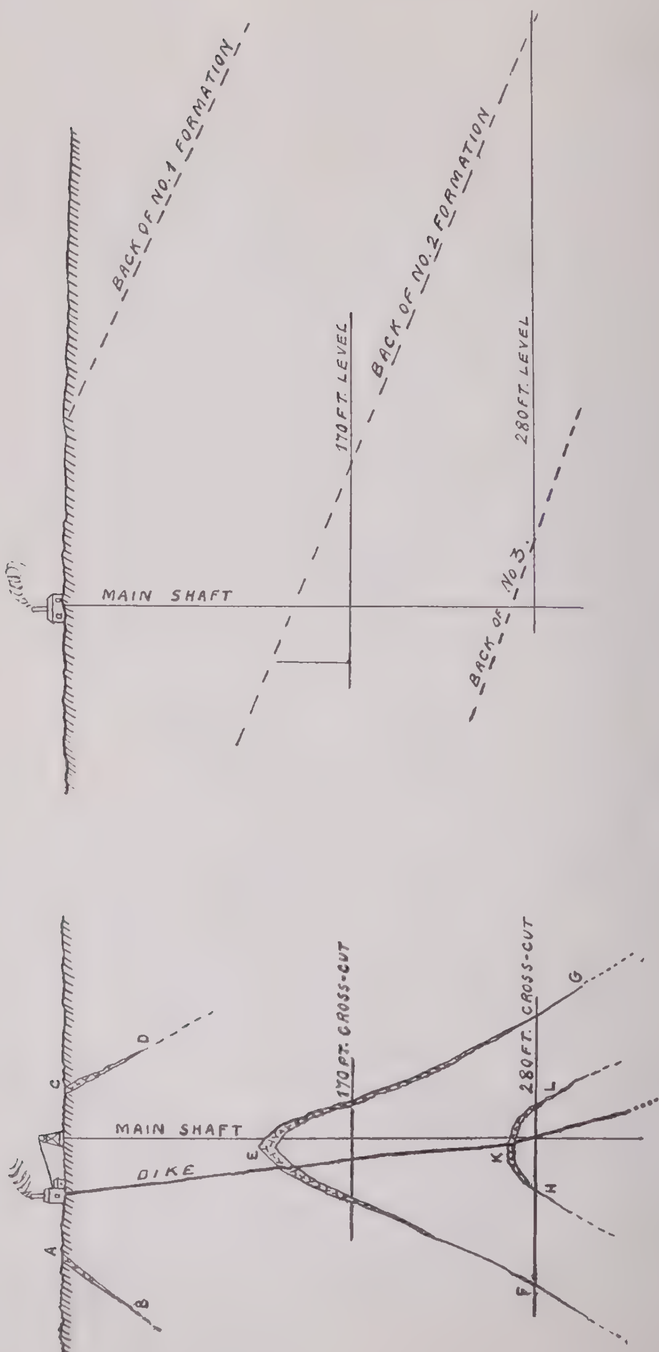


Fig. 4. South New Chum Mine.

ined. Erosion had left a rolling surface, the plane of which cut across the folds of the sedimentary rocks and across the interbedded quartz, so as to expose variously truncated portions of these peculiar ore deposits. The miner who found a big body of quartz, not knowing that it was the cap of a saddle, would sink through it into barren rock, while those who followed the fragments of legs, outcropping as veins, soon realized that they pinched in depth. It was disheartening. In several cases large combs of gold-bearing quartz were found standing boldly above the ground, thus giving rise to the term 'reef'. One of these, on New Chum hill, is shown in the accompanying photograph (Fig. 5) of a drawing made in 1851, the year in which Bendigo was discovered. But even this bold mass of rich ore did not continue into the solid rock with anything like the persistence to be inferred from such a showing at the surface. However, the miner is not easily discouraged. The prospectors at Bendigo, as elsewhere, did not cease to dig as soon as the ore pinched; they went deeper. Thus the men who sunk their shaft through the truncated apex of one saddle would eventually cut into the crest of the next one below, and those who were driving a cross-cut to intercept a leg on its dip would pass through the centre country, where a mass of ore might be found lying about another arch in the folds of the slate and sandstone beds. In the course of their work the miners got the idea of saddles in vertical succession. Having that, they were encouraged to explore continually deeper.

The three main lodes or 'lines of reef' are called the New Chum, Garden Gully, and Hustler's. Between them are minor anticlinal axes along which mining operations have exposed a less persistent series of 'saddles'. These geological conditions are associated with profitable mining over an area of 5 miles wide and 15 miles long. Of that area the most productive portion is a central tract of 8 square miles within which deep mining has been pushed with persistent energy to a maximum vertical depth of 4500 feet. The workings of individual mines tend to be restricted in lateral extension rather than in depth, because the ground owned by the separate companies is short along the strike, but ample in width, so that there is no territorial limit to sinking in the search for gold. Each of the 11 deep mines on Victoria hill, from Lansell's 222 to the Ironbark Quartz, covered (in 1891) an average of only 300 yards on the strike and owned an average of only 11 acres.

These conditions reflect the geological facts. In sinking, the

FIG. 5. BENDIGO IN 1851.

miner finds a nearly vertical succession of saddles, not all of which are sufficiently gold-bearing to be profitable. Thus the New Chum & Victoria had 30 saddles down to 2300 ft. But the 180 mine[5] down

[5]The Hundred & Eighty, and the Two-Twenty-Two mines are named according to the number of yards covered by the length of the claim.

to 2600 ft. is credited with five only, of which three have proved rich. The Lazarus cut 12 saddles between 850 ft. and 2000 ft., but two only have been exploited successfully. Such differences between the number of profitable saddles express economic rather than geological conditions, for all the saddles cut in the New Chum & Victoria extended into the ground owned by the 180 mine, and if they were not exploited in the latter it was due to local variations in the distribution of gold. The saddle was there and the gold was there, but not in sufficient quantity to constitute ore. Of course, the distribution of gold does not recognize imaginary boundaries, hence the same formation is worked throughout a succession of mines, north and south. In 1891 it was possible to walk underground from the Victoria Consols to Golden Square, through the connected workings of 21 mines, at a depth of 1800 to 2000 ft., for a distance of two miles. This indicates the persistence of ore along the strike. The continuity of the quartz is finally broken by overlapping of the saddles or by faults. It must be remembered that a bed of slate, representing a stratum of silt, has not the shape of a sheet of paper of indefinite size, but is more nearly a flat cone.

This gives an idea of the continuity of the gold-bearing quartz along the strike. Next comes the question as to persistence on the dip. This may be viewed from three aspects, according as the query refers to the two separate 'legs' of the saddle and its apex. The 'cap' or apex of a saddle is not often as regular as I have described it in the Johnson's mine. The sharp fold may culminate in a rupture along the anticlinal axis, creating a vertical fracture or a series of fractures along which the quartz is deposited in the form of a chimney. This upward extension from the cap has proved extremely rich in several mines. (See Fig. 6.) In the 222 mine above the 1900-ft. level, the cap of a saddle was prolonged for 81 ft. upward, finally breaking into veins and irregular embranchments. Similar conditions were exposed in the neighboring Lazarus mine, as illustrated in Fig. 7. Owing to later dislocations along the anticlinal axes, the apex of a saddle is subject to rupture and faulting. In the Victory & Pandora a fault crosses the orebody and causes a throw eastward; along the line of rupture quartz has been deposited, connecting the separated portions of the orebody and misleading the careless observer. In Fig. 8, the supposed conditions are illustrated on the left and the probable structure on the right. For the sake of comparison I add the cross-section (Fig. 9) of the neighboring Unity mine, in which the same fault is better developed, with results more obvious.

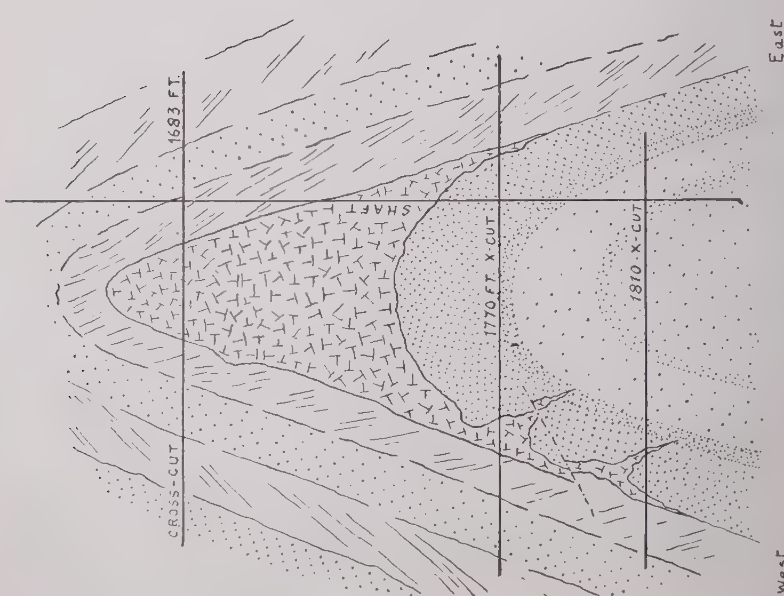


FIG. 6. NEW CHUM CONSOLIDATED MINE.

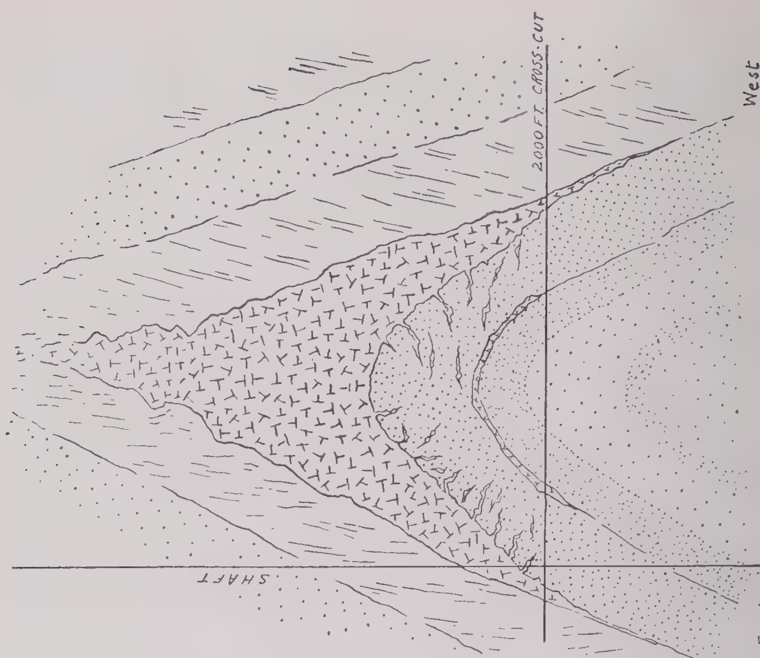


FIG. 7. 222 AND LAZARUS MINES.

The 'legs' exhibit the most variable persistence. In some cases only the apex of the saddle is rich enough, the downward prolongations of the arch proving unremunerative. The east legs are considered short-lived as compared to those on the west side, but it must be confessed that the evidence is not at all conclusive. A generalization is best avoided; the varying richness of the two members of the saddle is, I believe, regulated by local structural conditions independent of orientation. The most persistently rich east 'leg' was probably that in the Johnson's mine, which was stoped continuously for a depth of 400 ft. In the 180 mine an east leg was stoped vertically for 40 ft., while the "longest west leg" was 270 ft.; for in this celebrated mine the bulk of the gold obtained was extracted from ore at the apex of the saddles or just at the turn of the legs. In the same mine one saddle may have a rich west leg and a poor east leg, while in the next saddle, above or below, the conditions may be reversed. A leg that can be stoped for 200 ft. vertically is doing handsomely; one that can be extracted profitably for the distance (of 100 ft.) between levels is doing nicely. Thus the facts of mining emphasize the vertical non-persistence of the anticlinal masses of quartz. They exhibit ten times greater continuity in strike than in dip.

As viewed in a stope the leg of a saddle looks like any quartz vein conforming to the stratification of the enclosing rock. The ore often has a selvage of soft slate or else an edging of clay, which may widen into a 'gouge' seam. Enclosed country-rock, incompletely replaced by quartz and hinting at a sheeted type of fracturing, induces a streaky or 'ribbon' structure, such as characterizes the Mother Lode in California. If followed to successively deeper levels, the leg of a saddle will be found gradually to pinch until it narrows to a mere thread of quartz along the parting that indicates a plane of bedding. Even after the quartz disappears, the line of movement may be marked by slickensides or by a smear of clay due to attrition. The fracture coinciding with a leg may be continued above the saddle, as a tangent to its curve, in the form of a 'leader' of quartz or a 'back' that finally leaves the bent beds of slate and sandstone to traverse the country as a minor plane of faulting. Thus the same fracture in one mine plays many parts, serving to illustrate the fact that the mineral-bearing waters have utilized any way of passage that offered, with the result that the orebodies vary extremely in shape though alike in their origin. But before the genesis of these ore deposits can be discussed, other facts must be stated.

It might be expected that synclines exist between the anticlinal lodes. They do; in the Confidence Extended I saw several 'inverted' saddles, and in the Great Britain mine also. But these were small and unimportant. In the ground intermediate between the main anticlinal axes the bedding is often confused and shattered. Apparently the arch of the anticline has tended to perpetuate conditions favorable to the circulation of solutions, while the basin-shaped

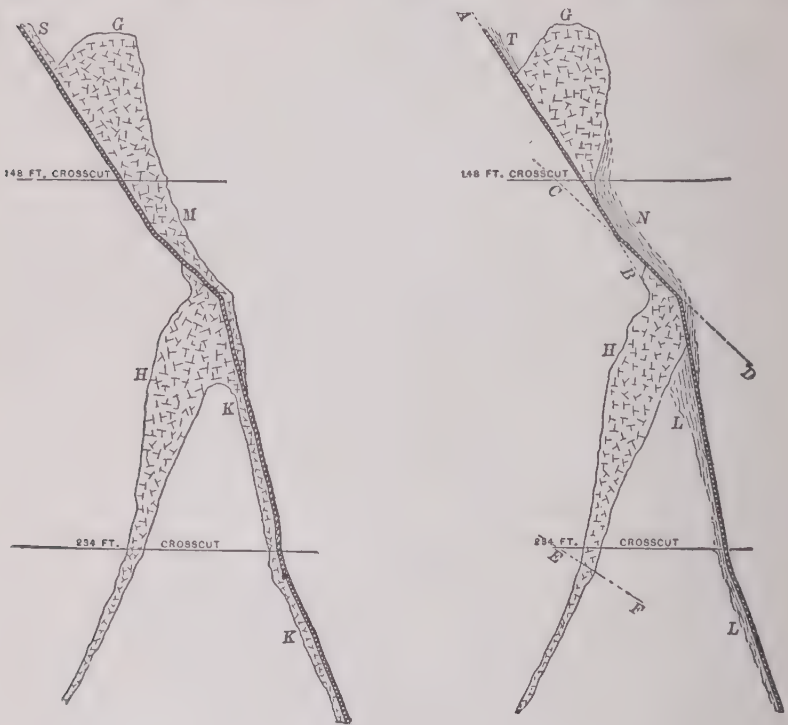


Fig. 8.

structure has led to the closing of openings essential to the movement of underground waters. Although the bedding is rendered indistinct by cleavage, especially in that part of the district where mining operations are most concentrated, it is possible to decipher the stratification by changes in the texture and color of the successive beds of slate and sandstone; but the best guide is furnished by ripple marks. In the Johnson's mine at the 1060-ft. level the surface of the bed of sandstone under the quartz exhibited beautiful rippling for more than 200 ft. in length and could be seen on the foot-wall of the stope for fully 100 ft. high. The preservation of

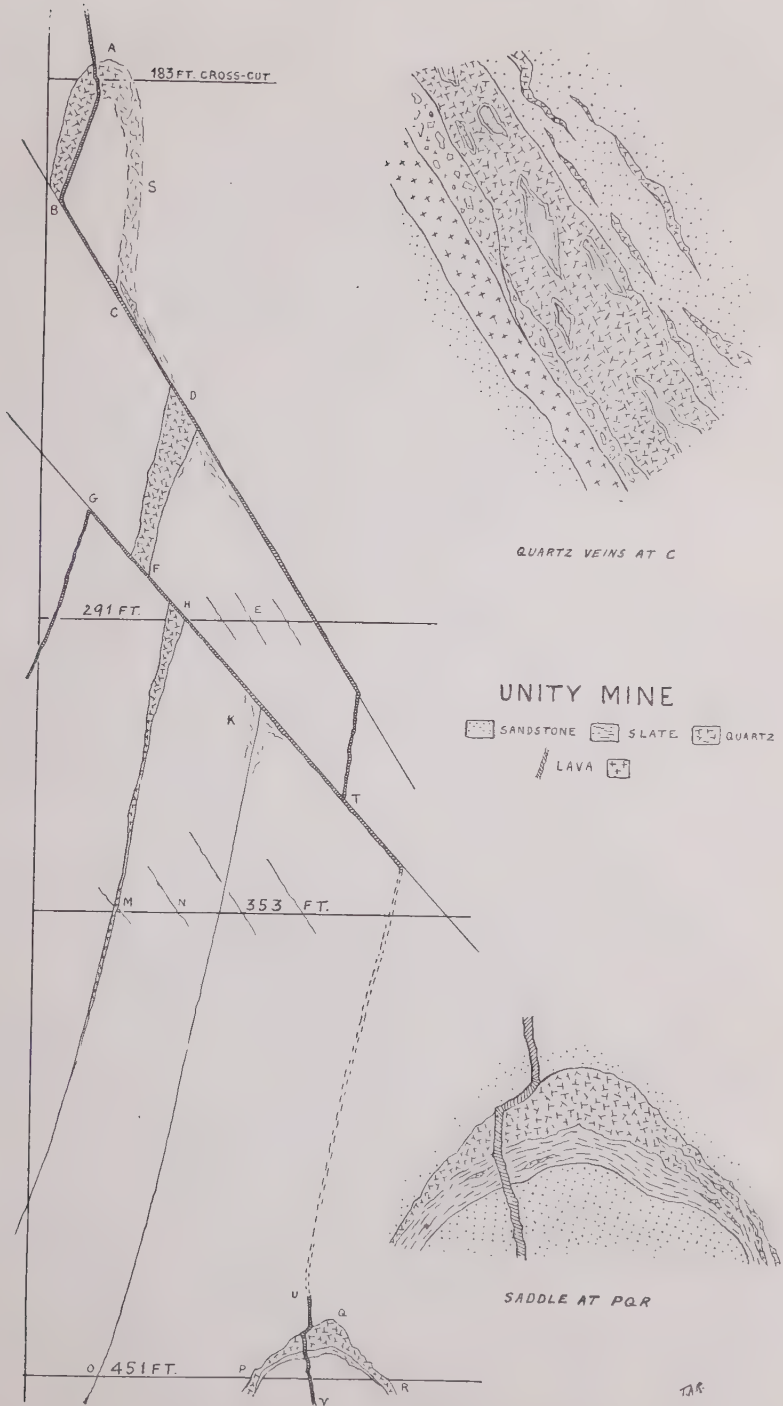

A
183 FT. CROSS-CUT
S
B
C
D
G
F
291 FT.
H
E
K
T
M
N
353 FT.
U
Q
O
451 FT.
P
R
V
QUARTZ VEINS AT C
UNITY MINE
SANDSTONE
SLATE
QUARTZ
LAVA
SADDLE AT PQR

FIG. 9.

the marks made by the wind in the shallow water of the Silurian sea is due to the fact that the fine sand was overlain by mud, now appearing as slate. At the 550-ft. level in the same mine I saw a bed of sandstone whose *under* side showed the *cast* of ripple marks, that is, the negative of the corrugated surface on which it had been deposited. Another interesting bit of testimony was obtained in some old stopes below the 1250-ft. level of the Lazarus mine. (See Fig. 10.) Under a well developed saddle I found some extremely delicate but distinct laminations in a fine-grained sandstone. The laminae, of varying shades of gray, were contorted so as to look like the section of a mountain range, and, in miniature, they represented the plication to which the exterior of the earth has been subjected. Fig. 11 is a drawing, to half-scale, of this exquisite ribboning; and in Fig. 10 the place where it is seen is indicated at *X*. The saddle is symmetrical save for the fault that cuts the east leg at *S S*. The bedding is indistinct, being hidden by a well developed radial cleavage (*A A*), but lines of fracture sympathetic to the bedding and marked by minute seams of quartz are discernible at *B B*. Rarely does a small section illustrate so many fundamental features in the local geology of a gold-mining district.

Another important feature is the presence of eruptive rock. This takes the form of thin dikes of lava, of basaltic character. The matrix is glassy, with microliths and skeleton crystals of amphibole surrounding grains of magnetite. A. W. Howitt labeled the rock 'limburgite'. It is an altered basalt that cooled rapidly. No feature of the Bendigo goldfield is more remarkable than the manner in which these 'lava streaks', as the miners call them, have found a tortuous passage through the great thickness of Silurian rocks. In the 180 mine a dike only 9 inches thick can be traced from the surface to 3500 ft. (See Fig. 12.) This three-quarters of a mile represents only a fraction of the distance it must have traversed, retaining a molten condition despite its small volume and the cooling effect of the adjoining wall-rocks. The lava is of Tertiary age, either Pliocene or post-Pliocene. It is identical in lithological character with the basalt that overlies and blankets the Miocene and early Pliocene alluvium in the neighboring districts of Clunes and Ballarat.

To those who look upon ore deposition as a phase of the thermal activity following in the wake of volcanic unrest, the existence of these small but marvelously persistent dikes is a fact most eloquent. In Fig. 12 a dike is shown breaking through successive saddles, searching a way near the anticlinal axis, deviating where passage was denied, following the bedding where it coincides with the general direction, but always finding some useful crack with patient persistence. In Fig. 4 another dike, almost in the exact line of

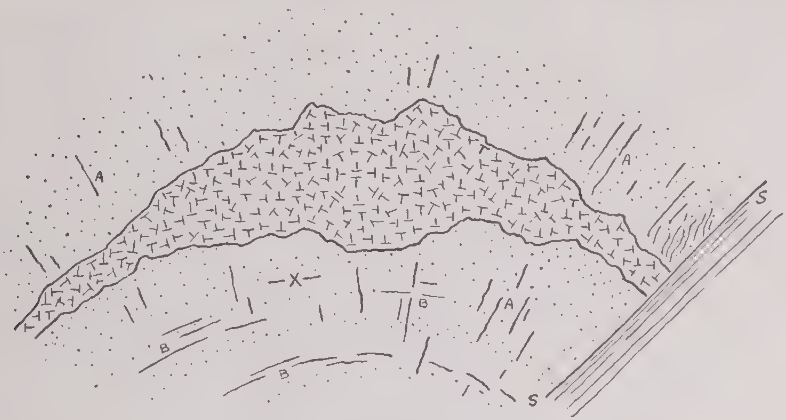
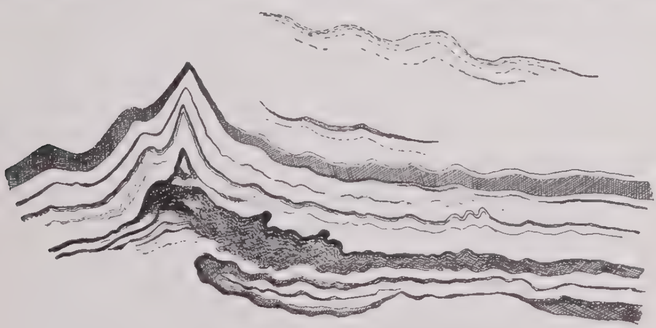


Fig. 10.

the anticlinal axis, is shown crossing three successive anticlines of quartz. In Fig. 9 more than one dike appears. The details of a crossing are shown at *P Q R* and the association with shattered quartz is indicated at *C*. In penetrating upward the dikes usually cross



CONTORTIONS IN SANDSTONE.
LAZARUS 1250 LEVEL

Fig. 11.

the saddles near their apex, where the rock is most fractured. The evidence of contact metamorphism is only faintly discernible on the quartz, the sandstone, and the slate; but it is not surprising that the physico-chemical effects should be slight, for the dikes constitute a relatively insignificant mass, and the mobility of the lava was due largely to hydro-thermal fusion. As soon as the edges cooled, a non-conducting envelope was formed, like the crust on smelter-slag.

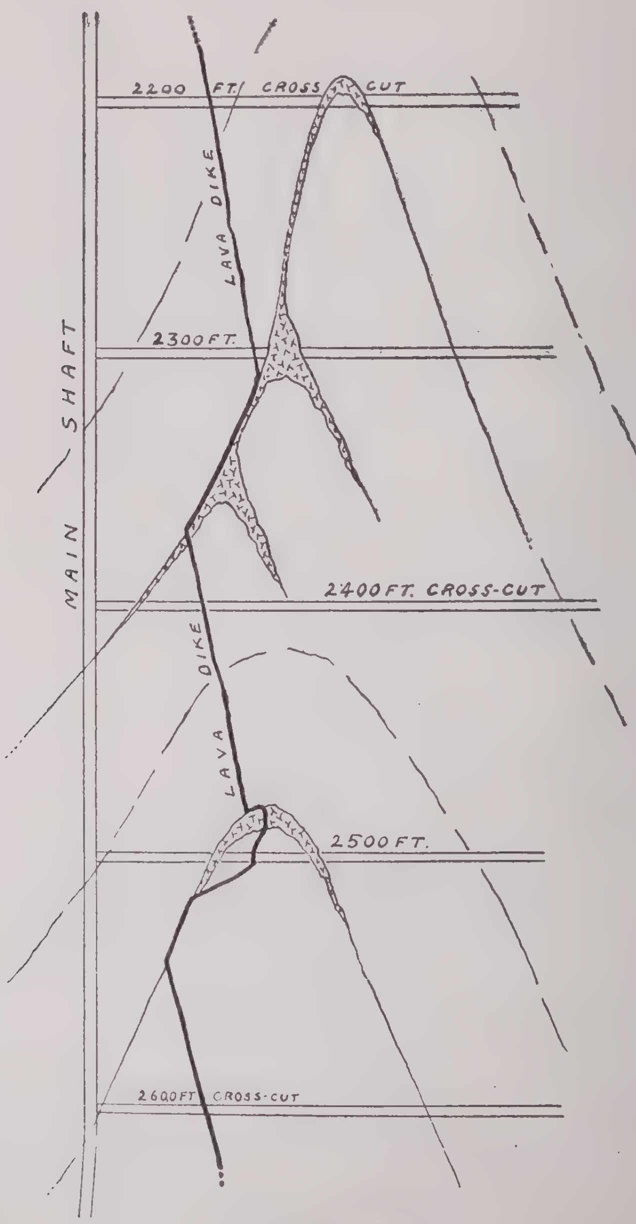


FIG. 12. 180 MINE.

The most productive portion of the goldfield is traversed by dikes; some of the richest ore is found near the intersection with dikes, but poor quartz also exists under similar conditions; gold has been seen on the dike-rock and in my collection I possessed (before the San Francisco earthquake-fire) several pieces of lava exhibiting free gold. Evidently the deposition of gold followed in part the irruption of lava. Thus we come to a theory explaining the distribution of quartz and gold. The facts disclosed appear to warrant the following conclusions:

The extreme plication of the Silurian rocks was due to earth-movements coincident with the extrusion of the granite; the regularity of the folds was rendered possible by the alternations of comparatively thin beds of slate and sandstone; after these had been folded the deposition of quartz began along the fractures and cavities created throughout the region, but chiefly at the crest of the folds and between beds of varying hardness, namely, under a bed of slate and over a bed of sandstone. On the principle of the arch there was a tendency to afford loose ground, if not actual openings, at the apex of an anticline; and the quartz was deposited in the slate for two reasons, namely, mechanically it was more pliant, and chemically it contained the organic matter, derived from vegetal remains, likely to facilitate precipitation of both the quartz and the gold. Once the first deposit had been formed the folded beds became stiffened and when the next disturbance ensued the tendency to break was stronger than the ability to bend. The deposition of gold-bearing quartz was probably intermittent; it represents a process of concentration, the gold and the quartz being derived from a deeper horizon within the earth, whence they were conveyed to the outer crust by the agency of magmatic waters. At a late period in geological time another marked movement in the earth's exterior was followed by the invasion of the lava in small but persistent streaks, like the water rising through thin cracks in ice. This had a sequel in thermal activity, in the irruption of mineral-bearing solutions, propelled by steam, and actively searching for lines of passage, which eventually became encrusted and filled with their valuable freight. The pitching crests of the anticlinal folds afforded the line of least resistance and stimulated the completion of the last phase of concentration whereby rich ore-bodies were segregated.

CONTACT DEPOSITS.

By James F. Kemp.

In the truly remarkable progress which has been achieved in the study of ores during the last ten or fifteen years, the subject of 'contact deposits' has played a prominent part. Though long unappreciated at their true significance, and regarded as merely subjects for interesting petrographic investigation, they are now recognized as one of the most important sources of copper and iron. The Southwest and Mexico possess well-nigh innumerable occurrences, and they do not fail in the Northwest, in British Columbia, and along the coastal districts of Alaska. Outside of North America they are not lacking, and it is always to be remembered that to the keen observational and interpretative powers of the Norwegian geologists is due practically their first recognition.[1] In the presentation of this subject, it will be my endeavor to first sketch briefly the types of contact zones which were early established by the petrographers, and then to summarize the theoretical views which were reached concerning them. The development of further views from later observations may next be outlined, leading naturally to the combination of petrography and economic geology in the latest investigations. There are some very interesting lines of attack which this particular problem has opened—lines which are fraught with much significance in relation to the large subject of the magmatic waters, and their influence.

By contact metamorphism is generally understood the processes of change which are set in action by an intrusive mass of molten rock and which work out their effects upon its walls. Recrystallization is started and new combinations of minerals form new and characteristic rocks. The effects are at a maximum next the intrusive, and die away in concentric zones or aureoles or halos as the observer goes outward. The intrusive mass itself does not escape,

[1] T. Kjerulf. 'Udsigt over det sydlige Norges Geologi, Kristiania, 1879.' This citation is taken from W. Lindgren's 'The Character and Genesis of Certain Contact-Deposits,' Trans. Amer. Inst. Min. Eng., 31, pp. 226-242, especially p. 230. Lindgren's paper was the first general one upon these ores in America and was of great influence in creating interest.

but almost always shows along its border the compact textures due to quick chill.

The extent or frequency of the metamorphism varies with different kinds of intrusives. It would obviously be more frequently seen and more extensively developed with magmas rich in dissolved vapors. The crystallization of these molten masses to the several anhydrous silicates, which make up the final rock, drives out the dissolved vapors as magmatic waters and provides thus a powerful agent of alteration along the borders. Acidic magmas or those high in silica are the rocks generally believed to be most richly provided with these so-called mineralizers, and as a matter of observation they are the ones around which are found the largest zones. Basic rocks are less likely to produce the changes, yet instances are known in which zones are associated with them. It is an interesting coincidence that cold, basic rocks have been found by Rollin Chamberlin to be the richest in gases.[2] Apparently the gases remain in the minerals of these rocks to a greater degree than in the acidic types. Again, large bodies of deep-seated rocks are more efficient agents than are small bodies, or than surface flows which only rest upon some underlying support and which soon lose their vapors into the atmosphere. On the whole, granites, with their close relatives, syenites, diorites, and the intermediate types, the monzonites and granodiorites, produce the largest zones.

Turning to the wall rocks, it is found that the zones are especially developed in two varieties of sediment, the richly aluminous, embracing the shales and slates, and the richly calcareous, the limestones. Sandstones are stubborn and unyielding subjects; while rocks already metamorphosed, such as gneisses and mica schists, have practically reached the limit of change. One therefore looks to the shales and slates on the one hand, and the limestones on the other, for the principal zones. The latter are more abundantly associated with ores than are the former.

The aluminous rocks develop a series of aluminous silicates of which andalusite, $Al_2O_3.SiO_2$, is most characteristic, so that the contact rock is often called an andalusite hornfels. Either with the eye alone or with the microscope, the fingerlike prisms of this mineral can be detected, and often the white and black crosses of the variety chiastolite appear in the dark hornfels. The home of chiastolite is in these zones. Other rather less characteristic minerals

[2]Rollin Chamberlin. 'The Gases in Rocks,' Publication 106, Carnegie Institute of Washington, 1908.

are sillimanite, $Al_2O_3.SiO_2$, staurolite, $(AlO)_4(AlOH)Fe(SiO_4)_2$, biotite, amphiboles of several varieties, and quartz. The zonal rock is often dense, black, and flintlike, suggestive of its name hornfels or hornstone. Sometimes, at a distance from the intrusive in the outer zones, are found the rude beginnings of crystals of andalusite or staurolite, or even only the segregation of pigments in spots, which have received the name of spotted schists or the local German terms of *fruchtschiefer*, *garbenschiefer*, etc., names scarcely capable of significant rendering into English. In North America the best known zone of this type is at Mount Willard in the White mountains. It was described in 1881 by George W. Hawes and will continue to furnish instructive exhibits to others while geology endures.[3] The zones are not lacking in the West, however, and of them more is certain to be heard from time to time. They do not fail in Europe, in the old mining districts of the Hartz and the Erzgebirge, but are seldom, if ever, productive of useful minerals.

The limestone zones are of greater interest. They yield a larger variety of minerals than do the aluminous rocks, and, aside from their connection with ores, are, on the whole, the most prolific of all mineral localities. The commonest minerals characteristic of them are lime-silicates of one sort or another, but these simple compounds can be varied by additions of other bases until a long series of minerals results. The most characteristic of all is garnet, once thought to be exclusively the variety grossularite, $3CaO.Al_2O_3.3SiO_2$, but now known to be more largely andradite, $3CaO.Fe_2O_3.3SiO_2$. With this, in almost as great amount, is diopside, $CaO.SiO_2.MgO.SiO_2$, while in less abundance or frequency we find wollastonite, $CaO.SiO_2$; epidote, $2CaO.AlO.OH.Al_2O_3.3SiO_2$; vesuvianite, $5CaO.MgO.Al_2O_3.AlO.OH.5SiO_2$; scapolite, $3CaO.2Al_2O_3.6SiO_2$ (variable); quartz, SiO_2; magnetite, Fe_3O_4; specular hematite, Fe_2O_3; and many more of lesser importance. As a group they are often distinctively called 'the lime-silicates.' The rocks range from coarsely crystalline to very dense, fine-grained varieties, whose minerals can only be determined by the microscope.

The so-called garnet-zones may be developed in strata next the intrusive, or they may spread outward along favorable beds for moderate distances,[4] or they may be developed around masses of

[3] George W. Hawes. 'The Albany Granite, N. H., and Its Contact Phenomena,' *Amer. Jour. Sci.*, Jan. 1881, pp. 21-32.

[4] Morrison B. Yung and Richard S. McCaffery. 'The Ore Deposits of the San Pedro District, N. M.,' Trans. Amer. Inst. Min. Eng., Vol. 33, 1903, pp. 350-362.

limestone which become torn off from the walls by the advancing tide of molten rock and which may be then corroded and worked over into the new minerals. Such blocks may be later cast out from the crater of a volcano and, as at Vesuvius, furnish a long list of minerals. If the included blocks are very large (some even attain the size of small hills) they may be surrounded by large enough zones to yield orebodies.

The commonest ore which is found associated with contact zones on limestone yields iron. The iron minerals magnetite and hematite seldom fail in any zone, and are often in masses of commercial size and purity. Practically all the iron ores of the Cordilleran region, except those at Hartville, Wyoming, are of this character. The best known are in the Iron Springs district of southwestern Utah, recently described by Leith and Harder,[5] but there are many more in the desert regions of southern California. The iron ores seem to have been brought from the eruptive rock during its cooling stages by magmatic waters and to have replaced the bordering limestone. They may also have been deposited in veins in crevices in the eruptive itself where they look like black dikes and by some observers are regarded as such.[6] Even if a deposit of any other metal had never been seen in the contact zones, the development of these iron ores would have shown this particular one to be a prolific emission from the cooling magmas.

Next after iron ores are those of copper. They are, as first precipitated, chiefly chalcopyrite or bornite in association with still larger amounts of pyrite. Alteration and secondary enrichment yield the usual train of higher sulphides and of oxidized products, but chalcopyrite and bornite seem to be the first members in the series. They and their attendant pyrite may fill crevices in the older iron ores, and may be mingled with the garnets and other silicates, but all three sulphides seem to follow the silicates and iron oxides in periods of deposition. The copper ores of first deposition are usually lean and of low grade. Secondary enrichment is needed in many cases to bring this first product up to a minable richness. Chrysocolla is, on the whole, the commonest product, but oxides and carbonates also appear, especially if there is calcite in the immediate vicinity. Instances are known, although not so common, in which the original sulphides are rich enough to smelt in the crude state.

[5] C. K. Leith and E. C. Harder. 'The Iron Ores of the Iron Springs District, Utah,' Bull. 338, U. S. Geol. Surv., 1908.

[6] E. P. Jennings. 'Origin of the Magnetic Iron Ores of Iron County, Utah,' Trans. Amer. Inst. Min. Eng., No. 35, 1903, pp. 338-342.

Copper ores from garnet zones are not well adapted to concentration. The high specific gravity of the gangue militates against a satisfactory separation. In the crude state, moreover, and unrelieved by secondary enrichment, these ores are usually too silicious for self-fluxing smelting, and when the copper is present as chrysocolla there is much danger of loss in the slag. The low tenor of copper makes the addition of barren material undesirable if it can be avoided. On the other hand, injurious ingredients are rare. Arsenic and antimony are unusual. A favorable feature is the characteristic but small percentage of gold, with which may occur 1 to 2 oz. of silver. The ores are irregular and fortuitous in their distribution in the zones. They may come in without warning, and they fade out in the same way.

There are one or two variations from the type of copper ores as just described. Whereas the usual experience is to find the copper disseminated in the zones of silicates, or in the associated bodies of magnetite, or in large individual masses of sulphides, at the mines of the Mazapil Copper Co., Aranzazu near Concepcion del Oro, Zacatecas, it favors large veins of coarse calcite that cut across the garnet zone outwardly from the intrusive into the limestone.[7] At the Cumberland-Ely mines in the Robinson district of Nevada, the lime silicates, while not entirely lacking, are much less abundant than in the cases cited. The zone is largely rusty chalcedonic and opaline silica within which, and well below the present surface, a great orebody has been discovered. This rusty silicious rock admirably illustrates those outcrops described in the West as 'blowouts.' In this instance silica seems to have replaced the limestone rather than to have combined with the lime.[8] The copper mines at Bisbee, Arizona, have also presented a case of contact zones that differs from the usual. Next the intrusive rock and over a width of about 200 ft. there has been developed a zone consisting of quartz and calcite, while outside of this and ranging over a width of approximately 1000 ft. the limestone is in large degree changed to a finely crystalline mass consisting of tremolite, pyroxene, garnet, vesuvianite, quartz, chlorite, and a few minor minerals. In this zone are situated the larger number of the orebodies, but some

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[7] J. D. Villarello. 'Le minéral d'Aranzazu (Etat de Zacatecas),' 10th Congr. geol. intern. Guide des Excursions, No. 25, p. 29, 1906. The statements in the present text are also based on my personal observations.

[8] A. C. Lawson. 'The Copper Deposits of the Robinson Mining District, Nevada,' Univ. California, Dept. Geol. Bull., Vol. 4, 1906 pp. 287-357. The statements in the present text are also based upon my personal observations.

occur still farther out in the almost unaltered limestone. F. L. Ransome, who has described the area, is inclined to attribute an important influence in the ore formation to one or two great faults which cross the contact-zones. The metamorphic changes seem less thorough in the Bisbee case than in many others, more calcite remaining in the end-product.[9] In the Velardeña district of Durango, Mexico, J. E. Spurr and G. H. Garrey have worked out an unusually complicated case in which in addition to the zones from limestone, a diorite has also developed along the borders into an aggregate of garnet and pyroxene. The common experience is to find the effects upon the eruptive itself limited to fine crystallization from chill.

A different type of orebody from all of these is supplied by the copper deposit at White Knob, Idaho. The garnet zones here appear as pipes or trunks within the mass of the eruptive, although not far from the contact. Ten different pipes outcrop, but they come together within 700 feet so that at the bottom levels there are but three or four surviving. The gangue of the ores is garnet, diopside, and calcite, as is usual, and in this case it appears as if calcareous hot waters had risen from below through the still heated eruptive and had produced the silicates.[10]

Iron and copper ores are, however, not the only ones found along the zones. Lead and zinc minerals were early noted in the Kristiania region and more rarely those carrying bismuth, antimony, and arsenic.[11] In Washington Camp, Arizona, copper has thus far been chiefly sought, but W. O. Crosby states that zincblende is more abundant[12] and galena is also well represented. In fact the complicated mixture of these several varieties has been one of the difficulties in the utilization of the ores of this particular locality. Zincblende is a rather common associate of copper ores in the zones. The mineralogy of the famous and unique orebody at Franklin Furnace, New Jersey, is much more closely akin to the contact zones than to any other known type, although it seems not to be in immediate association with a possible eruptive that could have produced it in this way. Gold associated with wollastonite has been recorded

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[9]F. L. Ransome. 'The Geology and Ore Deposits of the Bisbee Quadrangle, Arizona,' U. S. Geol. Surv., Prof. Paper 21, 1904. See also Bisbee Folio. A briefer account is in Trans. Amer. Inst. Min. Eng., 34, p. 618, 1904.

[10]J. F. Kemp and C. G. Gunther. 'The White Knob Copper Deposits, Mackay, Idaho,' Trans. Amer. Inst. Min. Eng., 36, pp. 269-293, 1907.

[11]T. Kjerulf, *op. cit.*

[12]W. O. Crosby. 'The Limestone-Granite Contact Deposits of Washington Camp, Arizona,' Tech. Quarterly, 18, pp. 171-190, 1905. Trans. Amer. Inst Min. Eng., 36, p. 632, 1905.

from the Santa Fé mine, Chiapas, Mexico.[13] It also occurs in the same relation, as I have observed, at the Cane Spring mine, in western Utah. Even platinum has been detected by L. Hundeshagen, with the same mineral in a contact zone, in Sumatra.[14] W. H. Weed has emphasized the sylvanite with less abundant native gold at Bannack, Montana.[15] The same observer found bismuth telluride (tetradymite) with bismuth sulphide (bismuthinite) at the Dolcoath mine in the Elkhorn district, Montana,[16] and also gold-bearing arsenopyrite at the Nickel Plate mine on the Similkameen river, British Columbia.[17]

It is evident from this review that the contact zones present a fairly wide range of metals, nevertheless it is true that copper has been the one of leading value hitherto. Iron, although somewhat utilized, remains chiefly for the future. Lead and zinc are known, but are not yet obtained in quantity from well established types. Gold has been found in several cases by itself, while it and a little silver are rather common associates of copper. Platinum has one recorded instance.

The contact zones, as stated at the outset, furnish particularly significant objects of study. The older idea of the formation of the silicates involved the re-crystallization of material in the original limestones without the addition of anything new. It was believed that where the zones are now found there was once a silicious, aluminous stratum, whose silica, alumina, and lime combined to yield grossularite or epidote; whose silica and lime gave wollastonite, or with magnesia, diopside, or with this and alumina, vesuvianite. Carbonic acid and water were evicted. Where small percentages of iron oxides appear in the silicates they were referred to the limonite or siderite molecules originally in the limestone. If a great eruptive dike or other form of intrusive cut across a series of limestone beds, and developed in some places the silicates, and elsewhere merely marbles, the inference was naturally drawn that in the former case the limestone was earthy or impure and the latter but slightly con-

[13]E. T. McCarty. 'Mining in the Wollastonite Ore Deposits of the Santa Fé Mine, Chiapas, Mexico,' Trans. Inst. Min. and Met., 4, pp. 169, 189, London, 1896.

[14]L. Hundeshagen. 'The Occurrence of Platinum in Wollastonite on the Island of Sumatra, Netherlands East Indies,' Trans. Inst. of Min. and Met., London, July 21, 1904.

[15]W. H. Weed. 'Ore Deposits Near Igneous Contacts,' Trans. Amer. Inst. Min. Eng., 33, pp. 715-746 (especially p. 732), 1903.

[16]*Idem*, p. 733.

[17]*Idem*, p. 734.

taminated.[18] In the interesting exposure at Washington Camp, Arizona, where there is some scattered chert in the limestone, rims of wollastonite were found by W. O. Crosby surrounding the still remaining inner masses of chert.[19]

Along these lines a very interesting and important study was carried out by Joseph W. Barrell[20] both for aluminous and calcareous zones. Assuming the raw materials to be in the limestones with which the metamorphosing agents must work, and that they were calcite, magnesite, kaolinite, and limonite, it was possible to calculate the amounts of these which would be needed for the production of grossularite, diopside or other silicates and the amounts of carbonic acid and water which would be driven off. By dividing percentage compositions by specific gravities, ratios were obtained, proportionate to the volumes of the several minerals, before and after. The number of volumes lost in the change could be computed and it was found to be impressively large. Thus in the production of grossularite, from calcite, kaolinite, and quartz, the lost carbonic acid and water and the increased specific gravity of the garnet involved 46.9% of cavities in the new rock, unless compression were to diminish them. Diopside necessitated 42.4% and wollastonite 32.8%. In the aluminous rocks andalusite would leave 27%. In Barrell's view porous belts of rock were thus afforded in which circulating solutions might later deposit ores. The hypothesis may, however, be tested in several ways: (1) What was the composition of the original limestone and did it contain the necessary ingredients for grossularite and the other lime-silicates? (2) Is the garnet of the zones actually grossularite? (3) Do the zones show the cavities that these calculations call for? (4) Do the silicates first form, producing cavities which are later filled by the ores?

The composition of the original limestone can be determined at least approximately by samples taken from the same bed or stratum at a distance from the eruptive. This has been done at San Jose, Tamaulipas, Mexico,[21] and at Morenci, Arizona.[22] In the first case there was less than 1% ferric iron and alumina and only 4 to 5%

[18]Joseph Barrell. 'Microscopical Petrography of the Elkhorn District, Montana,' U. S. Geol. Surv., 22d Ann. Rept., Pt. 2, p. 546, 1901.

[19]W. O. Crosby, *op. cit.*

[20]Joseph Barrell. 'The Physical Effects of Contact Metamorphism,' *Amer. Jour. Sci.*, pp. 279-296 (especially p. 288), 1902.

[21]J. F. Kemp. 'The Copper Deposits at San Jose, Tamaulipas, Mexico,' Trans. Amer. Inst. Min. Eng., 36, pp. 178-203 (especially p. 189), 1906.

[22]W. Lindgren. 'The Copper Deposits of the Clifton-Morenci District,' U. S. Geol. Surv., Prof. Paper 43, pp. 27, 375, 1905.

silica. The samples were taken in the endeavor to get a fair indication of the general composition. It certainly would not seem possible to conclude that grossularite in wide zones could have resulted solely from a limestone of this composition. At Morenci, the Modoc limestone, which is the one chiefly converted into garnet, is shown by Lindgren's analyses to have less than 2% silica and less than 3% alumina and ferric oxide. George Smith in the Chillagoe district of Queensland records limestones of 1.25% silica and less, and of less than 1% alumina and iron oxides.[23] So far as these analyses are significant, it is again obviously unreasonable to expect zones of almost solid garnet, several hundred feet wide[24] to be formed by the re-crystallization of an original of anything like this composition.

Hydraulic limestones are indeed known and are extensively used for natural rock cement. They range from 25 to 37% silica, 7 to 17 alumina, and 1 to 5 ferric oxide, and so far as chemical composition is involved they might yield grossularite, diopside, and other silicates, but they are rather unusual rocks as limestones run, and their presence should be demonstrated in each particular case rather than assumed. The presumption and such evidence as is available in the way of analyses, are against their presence.

In answer to the second query as to whether the garnet is really grossularite, the lime-alumina variety, there is even more significant evidence. In the San Jose case, the garnet proved on analysis to be over 60% andradite, the lime-iron variety. In the Morenci instance it proved to be almost pure andradite.[25] The garnet from Washington Camp has also been found on analysis to be predominantly andradite. While it is greatly to be desired that these analyses may be multiplied as time goes on, and that samples may come from many additional localities,[26] enough evidence is at hand to justify the conclusion that the unquestioned assumption of grossularite is unwarranted. Now, while it might be possible with apparent justice to reason about a supposed limestone high in alumina, it is a very different matter to assume one high in iron. Richly ferruginous limestones are almost unknown, and thus a strong presumption is raised against the re-crystallization of material solely

[23]George Smith. 'The Garnet Formations of the Chillagoe Copper Field, North Queensland,' Trans. Amer. Inst. Min. Eng., 34, pp. 467-478, 1904.

[24]W. Lindgren, *op. cit.*

[25]W. Lindgren, *op. cit.*, p. 134.

[26]George Smith *op. cit.*, p. 475. An analysis is given of garnet, but there must be other minerals present, as the analysis cannot be recast for grossularite and andradite alone.

derived from the limestone. In the White Knob case where the pipes of garnet rock were in the eruptive, two analyses showed respectively 69.26 and 47.82% grossularite, with 21.13 and 44.16 andradite. These results, while higher in the aluminous variety, were by no means lacking in the ferruginous, even when the wall-rock of the pipes ran 16 alumina and only 1.59% of both oxides of iron.

The third query as to whether as abundant cavities are found in the garnet zone as the calculations call for is to be answered by observation. The theoretical abundance could hardly be expected to be actually reached. No zone is pure garnet. Diopside, and epidote or other lime silicates whose production involves fewer cavities, are seldom if ever lacking. There is also more or less calcite, and there may be not inappreciable quantities of quartz. Yet after critical observation of several zones with this point in mind I have felt that the cavities were not as abundant as would be rightly expected on the re-crystallization hypothesis, but that there are often belts several feet wide of very dense rock. Vugs and cavities do occur, but they are too few in number. If cases like the zone of the Cumberland-Ely mine in Nevada, be examined, zones are found that are so largely pure silica that the re-crystallization hypothesis can hardly apply. To a less but still appreciable degree it is difficult to use it for diopside, a mineral higher in silica than the garnets, or for wollastonite, which is likewise more silicious. From only a few per cent in silica, ten or less, can hardly be believed to have been produced a rock that is either almost pure silica or composed of silicates fairly high in this acid radical.

In several localities the succession of the minerals in the zones has been worked out both by means of microscopic slides and by study of the hand-specimens. In the San Jose case the order seemed to be the following, the only question being the time relations of the lime silicates and the magnetite: (1) diopside and garnet; (2) magnetite; (3) pyrite and chalcopyrite. At Morenci, Lindgren records the simultaneous crystallization of the lime-silicates and magnetite together with some of the sulphides, whereas other sulphides are clearly later and cut the earlier minerals in veinlets. At the White Horse Pass mines in the Yukon, O. Stutzer determined the following order: (1) pyroxene, and rarely magnetite; (2) magnetite; (3) garnet with a few metallic sulphides; (4) amphibole and the greater part of the sulphides; (5) calcite.[27] Stutzer cites in this same paper

[27] O. Stutzer. 'Die Kontaktmetamorphen Kupfererzlagerstaetten von White Horse, Yukon,' *Zeitschr. für prakt. Geol.*, March 1909, p. 120.

the observations of O. E. Leroy upon the deposits of Texada Island in which the pyroxene precedes the sulphides, but the relations of the latter to the garnet are not mentioned. In some detailed observations upon garnet zones at Velardeña, Mexico, J. E. Spurr and G. H. Garrey note a number of successions in all of which the formation of garnet or some other lime-silicate comes first and the entrance of the metallic minerals follows.

These cases fall in line well with Barrell's view that the metallic minerals might be deposited in a porous rock, made so by the recrystallization of the limestone, but it is fair to say that they might also leave the eruptive at a somewhat later stage than the silica, iron, and alumina and continue the replacement of the limestone or might fill any cavities that had resulted when silica and its associates evicted carbon dioxide. Magnetite and hematite occur in such great bodies and are so clearly replacers of limestone that the introduction of iron oxide from the intrusive mass seems established beyond question.

Not every observer has been inclined to view the garnet zones as contact effects. Some have thought them intrusive masses themselves. George Smith, in describing the Chillagoe, Queensland, occurrence mentions garnet rock 200 ft. wide enclosed in granite and regards this as well as occurrences along the border of the granite and limestone as intrusive in nature. Most geologists, however, favor the hypothesis of production of the garnet by contact metamorphism and would be inclined to interpret the mass wholly enclosed in granite as a great limestone fragment altered by the eruptive or as formed in some such pneumatolitic manner as is necessary to assume for the White Knob, Idaho, case. Not a few observers in the field have doubtless speculated on the possible absorption or in-fusion of limestone along the border of the intrusive rock, and wondered if at the time of its entrance the intrusive mass were not sufficiently superheated to make this possible. There is, however, as a rule, a pretty sharp line of demarkation between eruptive and sediment and there is also a gradual passage of garnet or other lime-silicate rock into limestone. Scattered garnets and pyroxenes gradually fade out into barren wall-rock. Some rather well-grounded objections to garnets from fusion have been found in artificial experiments. Thus if garnet of the grossularite type be artificially melted and the crucible allowed to cool slowly, not garnet, but a mass of anorthite, melilite, and pyroxene results. E. T. Allen and W. P. White have made some interesting demonstrations of the melting point and conditions of possible existence of wollastonite, one of the commonest contact minerals.[28] They find that at normal pressures wollastonite cannot exist above 1180°C. At higher temperatures pseudo-wollastonite results, a mineral of a different crystal system and one not known in nature. While it is possible that higher pressures may make differences, yet the fusing point of acidic eruptives is usually well above 1200°C. and the intrusive masses may have been much higher. Wollastonite does form at normal pressures as low as 860°C. There is some reason thus to think it not a product of crystallization from fusion, but the result of the still highly heated after-effects. The banded arrangement of the lime-silicates, moreover, the vugs with their coats of crystals, the veinlets of sulphides, of quartz, and of calcite itself, all argue against fusion and in favor of pneumatolitic processes.

Thus it has come to pass that almost all the recent students of these contact phenomena have interpreted them as due to the emission of water-gas and other highly heated vapors, which with continued fall in temperature in time give rise to highly heated waters. Where to draw the line between the two physical forms is scarcely known. The further speculation seems justified, that if the issuing gases and waters do not encounter limestones or aluminous rocks and are not relieved of their dissolved elements near the intrusive mass, they may rise as hot-springs and with diminishing pressure and temperature fill veins in the upper rocks. The abundant silica of the contact zones and its predominant occurrence as a gangue in the fissure veins are two things that may be of complementary significance.

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[28]E. T. Allen and W. P. White. 'On Wollastonite and Pseudo-wollastonite,' *Amer. Jour. Sci.*, Feb. 1906, p. 89.

THE CONGLOMERATES OF THE WITWATERSRAND.

By F. H. Hatch.

Discovered in 1885, the growth of the Witwatersrand goldfield, in the Transvaal, was at first slow. The earliest workers thought that the auriferous gravels, exposed only to a small depth in shallow pits and open workings, were superficial deposits similar to the alluvial placers of California and Australia. Once it was realized, however, that they were the outcrop of true beds of conglomerate inter-stratified with sandstone[1], claims on the dip were pegged out; shafts were sunk; and by 1887 stamp-mills were in operation, the value of the output from the Witwatersrand mines for that year being £81,045. Since then progress has been rapid, as will be seen from the table opposite.

Down to the permanent water-level at from 100 to 200 ft., which represents the vertical variation of the zone of weathering, the conglomerate beds have the appearance of gravel and consist of well rounded pebbles of quartz lying loosely in a red clayey matrix. Below the water-level the color changes from red to blue: the orebodies become pyritic; and the gold is no longer as amenable to recovery by amalgamation as in the oxidized ore. Since the introduction of the cyanide process in 1890, however, the pyritic nature of the ore has opposed no great difficulties to the extraction of the gold; it having been ascertained that by grinding to a sufficient degree of fineness the noble metal is liberated from its intimate association with iron pyrites and may be successfully removed by a weak solution of potassium cyanide. It is no exaggeration to say that the great success of the Witwatersrand gold industry is the direct result of the cyanide process. To the majority of the mining companies the gold recovered by this process represents the difference between profit and loss, for without cyanidation it would be impossible to work successfullly the vast quantity of low-grade banket[2] now being mined on the Rand. There

[1] Which below the zone of weathering exist as quartzite.

[2] 'Banket' is a Dutch word locally applied to the conglomerate on account of its supposed resemblance to an almond-cake made by the Boers.

is an enormous quantity of this banket, containing an average gold content of about 5 dwt. per ton, and it is becoming apparent that, with the extension of the scale of operations and consequent reduc-

TONNAGE CRUSHED AND VALUE OF GOLD RECOVERED FROM THE WITWATERSRAND MINES FROM 1887 TO 1910.

	Tons crushed	Value of Gold recovered.	Shillings per Ton.
1887	[Not recorded, say 1,000,000]	£ 81,045	[42·2]
1888		729,715	
1889		1,300,514	
1890	702,828	1,735,491	49·4
1891	1,175,465	2,556,328	43 4
1892	1,921,260	4,297,610	44 7
1893	2,215,413	5,187,206	46 8
1894	2,827,365	6,963,100	49·2
1895	3,456,575	7,840,779	45 2
1896	4,011,697	7,864,341	39 2
1897	5,325,355	10,583,616	39 7
1898	7,331,446	15,141,376	41 3
War period 1899	6,639,355	14,093,363	42·4
War period 1900	[Not recorded, say 1,000,000]	2,484,241	[49·7]
War period 1901	412,006	1,014,687	49·2
War period 1902	3,416,813	7,179,074	42·0
1903	6,105,016	12,146,307	39·8
1904	8,058,295	15,539,219	38·5
1905	11,160,422	19,991,658	35·8
1906	13,571,554	23,615,400	34·8
1907	15,523,229	26,421,837	34·0
1908	18,196,589	28,810,393	31·6
1909	20,543,759	29,900,359	29·1
1910	21,432,541	30,703,912	28·6
	156,026,983	£276,181,571	35·4

tion of the cost of working, the bulk of this ore will be mined.[3] But the gold content of the Rand conglomerate is not so evenly distributed as has been supposed. The sheets of conglomerate include areas, of irregular form and extent, of higher grade ore; and in the early years this alone was sought after, the low-grade material being passed over as unprofitable.

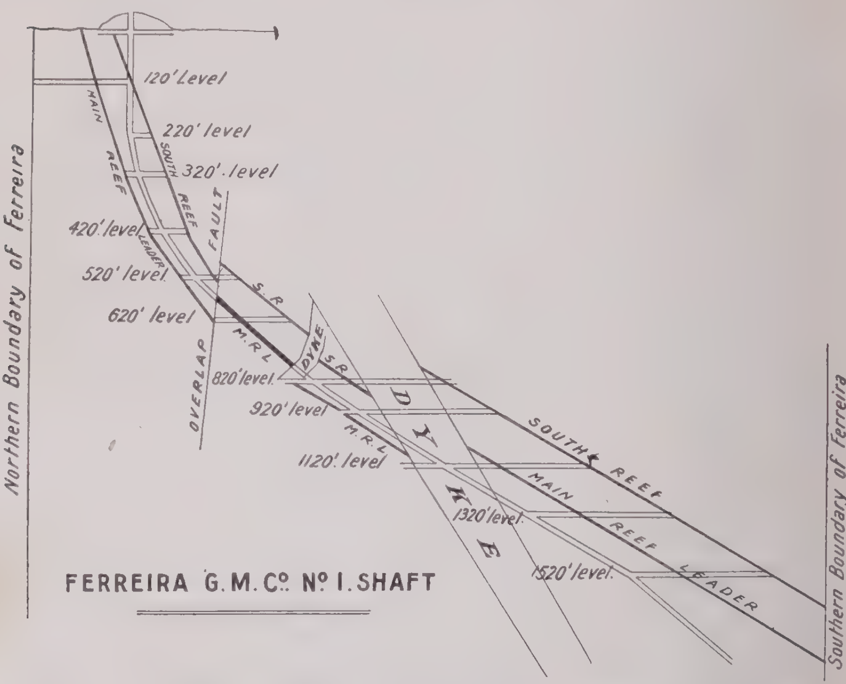

FIG. 1. TRANSVERSE VERTICAL SECTION THROUGH FERREIRA MINE ON THE CENTRAL RAND. A TYPICAL OUTCROP MINE.

As is usually the case in a new district, situated at a great distance from a seaport and as yet untouched by railways, with an uncertain supply of indifferent labor, and machinery and stores only obtainable at a prohibitive rate, the operating cost was at first high, so that a profit could be obtained only by limiting exploitation to the high-grade ore. In the table given above it will be seen that the value of the gold recovered has decreased from £2 10s. (12 dwt.) per ton milled in 1890 to £1 8s. 6d. (6.8 dwt.) in the year 1910. This is, in the main, due to the lowering of

[3] Compare F. H. Hatch, 'The Past, Present, and Future of the Gold-Mining Industry of the Witwatersrand.' James Forrest Lecture, Inst. C. E., 1911. (Abstract in *Mining and Scientific Press*, July 22, July 29, 1911.)

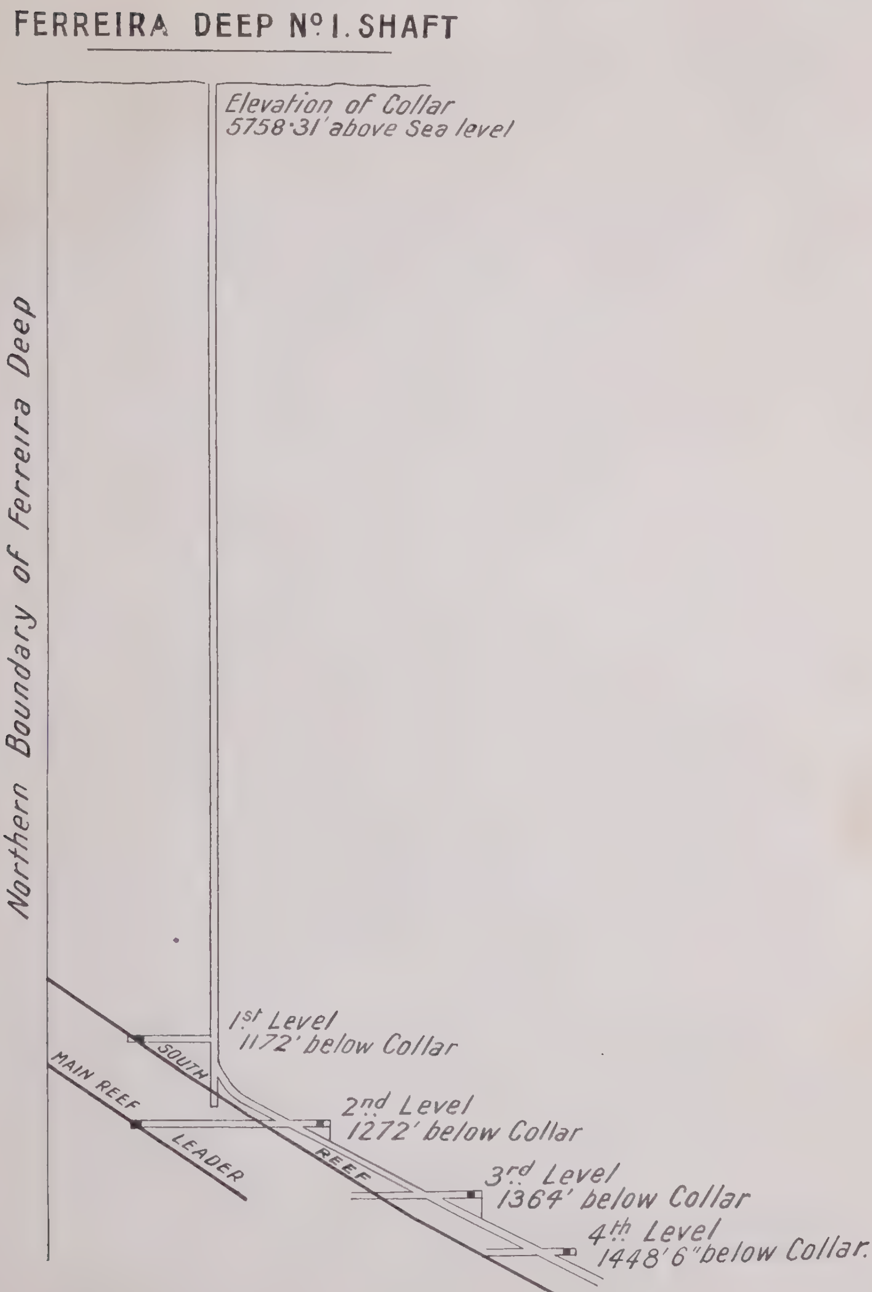

FIG. 2. TRANSVERSE VERTICAL SECTION THROUGH THE FERREIRA DEEP MINE ON THE CENTRAL RAND. A TYPICAL DEEP-LEVEL GOLD MINE.

the operating cost, which enabled large areas of relatively poor ore to be exploited that were formerly considered outside the range of practical mining. It is of course possible that the average value of the orebody *per se* has also decreased slightly with increased depth, but on the data available it is difficult to say whether this is so or not, owing to the irregular distribution of the high-grade patches. During 1910 the operating cost, according to the Witwatersrand Chamber of Mines, averaged 17s. 7d. per ton, but 25% of the whole body of ore crushed was worked at an average cost of a little under 14s. per ton, thus yielding a profit on all ore above 3¼ dwt. The deepest workings at present are at 4000 ft. vertical; but the mines are being laid out to work at 5000 and 6000 ft., and there is little doubt that, should the ore warrant it, the workings will be extended to an even greater depth. The published statements of 36 companies show that their ore reserves, blocked out at the close of 1910, amounted to over 80,000,000 tons and that their average value was 6.3 dwt. per ton.

The geological formation in which these auriferous conglomerates occur is known as the Witwatersrand system. It consists of a group of sediments some 20,000 ft. thick, and separated by a great unconformity from the old schists and conglomerates of the underlying Swaziland system. Since no fossils have been found, the age of the formation is not known, but it is certainly of great geological antiquity, since it is separated from the base of the Waterberg sandstone (the equivalent of the Table Mountain sandstone, which is of early Devonian age) by 25,000 ft. of strata and by more than one great unconformity. It is therefore probably of pre-Cambrian age; and it has been suggested (but without any real basis for correlation) that it is the South African equivalent of the Algonkian of North America.[4]

The rocks composing the Witwatersrand system consist of conglomerate, grit, quartzite, and slate. The conglomerates contain round and sub-angular fragments of quartz and quartzite (the former greatly preponderating), in a matrix of quartz grains, the whole being cemented to a hard and compact rock by secondary silica. The quartzites, which were originally deposits of quartz sand, owe their quartzitic character partly to metamorphism by pressure and movement, partly to the deposition of secondary silica. The slates also consist largely of quartz in minute fragments with

[4] J. W. Gregory. Report of the Committee of the British Association appointed to investigate and report on the correlation and age of South African strata, 1910.

a sericitic variety of mica which is especially developed in those portions of the beds that have undergone differential movement. Some of them contain abundant hair-like needles of rutile.

The position of the Witwatersrand rocks in the South African succession is as below:

System.	
Karroo	(With the basal Dwyka conglomerate)
(Unconformity)	
Waterberg	(Table Mountain sandstone of the Cape)
(Unconformity)	
Potchefstroom	Pretoria Series Dolomite Series Black Reef Series with basal conglomerate
(Unconformity)	
Ventersdorp	Volcanic lavas and breccias, boulder beds, and conglomerates (Elsberg series)
(Unconformity)	
Witwatersrand	Upper and lower divisions
(Unconformity)	
Swaziland	Schist and granite

This system is divided into an upper and a lower division, the upper being characterized by numerous beds of conglomerate and a few beds of slate, the lower by many beds of slate and a few of conglomerate. The division is made at the base of the auriferous conglomerates known as the Main Reef series; but, since there is no unconformity, this is merely a matter of convenience.

The Lower Witwatersrand beds are well exposed in the range of hills that bounds the gold mines to the north, from Boksburg to Krugersdorp. These hills are the highest portion of the elevated tract of country known as the Witwatersrand, or briefly the Rand, and constitute the water-parting between streams tributary to the Limpopo river on the north, and those tributary to the Vaal on the south: the former discharging into the Indian Ocean; the latter, first in the Orange river and, finally, into the Atlantic. The range has an abrupt escarpment,[5] facing north, but slopes gradually

[5] This is the real Rand, this Dutch word being used in the sense of the word 'escarpment.' Thus Witwatersrand means white-waters-range.

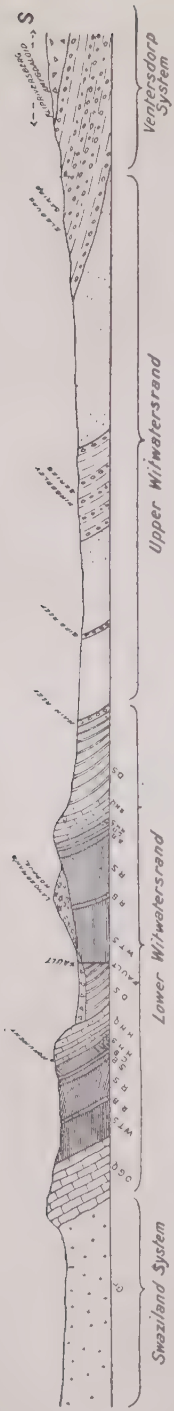

FIG. 3. SECTION BY F. H. HATCH ACROSS THE WITWATERSRAND BEDS (north to south.) The section is drawn along the line A-B on the geological map of the district around Johannesburg, plate II.

southward to the outcrop mines. A section taken across the beds immediately to the north of Johannesburg shows four or five ridges of quartzite, alternating with broader belts of slate, which, on account of their inferior resistance to agencies of denudation, as a rule form shallow depressions or valleys. The beds dip southward at angles varying from 45° to 85°, the total width of the outcrop from the granite to the Main Reef conglomerate being a little over two and a half miles.

The following table gives the thickness of the different members of the Lower Witwatersrand beds, as shown in a section at Brixton across the beds from the Main Reef to the granite[6]:

	Subdivision.	Feet.
9.	Red Bar	450
8.	Doornfontein Beds (slate and quartzite)	5,500
7.	Hospital Hill Quartzites	1,400
6.	Hospital Hill Slates	620
5.	Speckled Bed	20
4	Red Slate	1,800
3.	Ripple-Marked Quartzite	60
2.	Water Tower Slates	1,400
1.	Orange Grove Quartzites	1,400
		12,650

In the Bezuidenhout valley, east of Johannesburg, a portion of these beds, namely, from the Ripple-marked quartzite to the Doornfontein slates, is duplicated by a great reversed fault or overthrust[7] (see Fig. 3).

[6] Hatch and Corstorphine. 'The Geology of South Africa,' Landon, p. 124.

[7] A similar duplication of the Upper Witwatersrand beds occurs in the East Rand; in that district there is a double outcrop of the Main Reef conglomerates and both portions are worked, the northern workings being limited on the dip by the reversed fault which has caused the duplication.

In the Upper Witwatersrand, quartzites largely predominate, forming the bulk of the whole series. The slate beds are, with one exception (that underlying the Kimberley series) quite insignificant; and the conglomerates are plentiful only in certain well defined

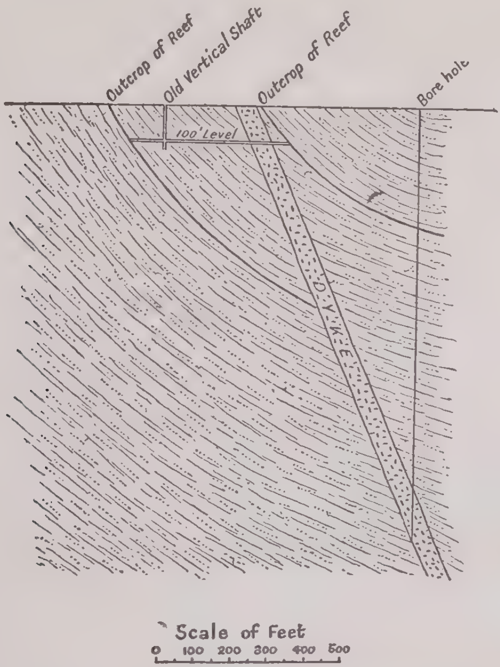

FIG. 4. DOUBLE OUTCROP OF THE MAIN REEF SERIES PRODUCED BY OVERTHRUST FAULTING, WITWATERSRAND MINE, EAST RAND. Note that a dike has been intruded along the fault plane. (Section by F. H. Hatch.)

zones, which are conveniently grouped under the following names, originally given them by the gold prospectors:

4. Kimberley Series.
3. Bird Reef Series.
2. Livingstone Reef Series.
1. Main Reef Series.

The total thickness from the base of the Main Reef series to the unconformable overlying Ventersdorp system is about 7000 ft., while the lower division of the Witwatersrand system from the base of the Main Reef to the top of the Swaziland system is about 12,000 ft., making a total thickness of 19,000 feet.

Boreholes put down in the central portion of the Rand give the following successive and average thicknesses for the different beds:[8]

	Feet.
Kimberley Conglomerates	1200
Slates	900
Quartzites	290
Bird Conglomerates	450
Quartzites	470
Livingstone Conglomerates	250
Quartzites	900
Main Reef Conglomerate	90
	4850

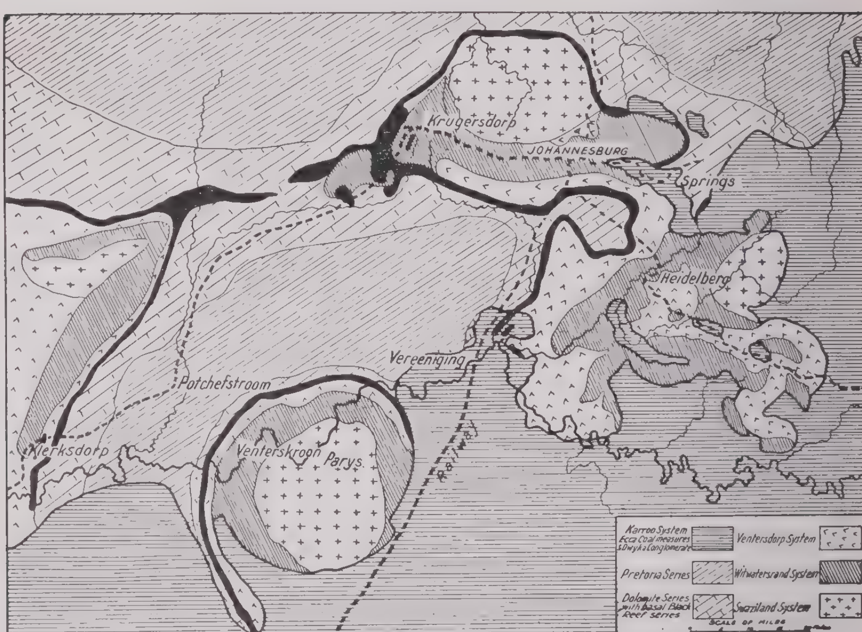

FIG. 5. GEOLOGICAL MAP OF THE SOUTHERN TRANSVAAL.
(Reduced from a map by F. H. Hatch, first published in 1897.)

The strike of the beds of the Rand proper is east and west, the dip to the south, at a steep angle near the outcrop but averaging about 25 degrees in the deep-level mines. Johannesburg lies immediately north of the outcrop of the Main Reef, about half-way

[8] Hatch and Corstorphine. 'Geology of South Africa,' London, 1909, p. 34.

between the east and west limits of the mines at present worked, namely at Randfontein, 25 miles west, and at Springs, 25 miles east of the centre of the town. Beyond these points the extension of the Witwatersrand beds is covered unconformably by the dolomite of the Potchefstroom system;* but bore-holes put down east of Springs have traced the sub-outcrop of the beds to a point 10 miles to the southeast, where they re-appear at the surface with a northwesterly dip, showing that we have here to do with the concealed eastern end of a synclinal trough.[9] The axis of this syncline strikes from a point midway between Springs and Nigel, in a southwesterly direction toward the town of Potchefstroom; and the outcrop of the Witwatersrand beds, forming its southern limb, is found on the Vaal river, 15 miles to the southeast of Potchefstroom. The dip, however, of these Vaal River conglomerates is not north, as it should be, owing to an overfolding of the formation. But the beds succeed one another in the proper order, the lower beds outcropping south of the upper beds. The width of the syncline at the surface, from the outcrop of the Main Reef on the Witwatersrand to the corresponding horizon in the Vaal River series, is about 45 miles.

The Main Reef series has been worked for its valuable gold content more or less continuously for a distance of 46 miles. The comparison of sections, taken through the series at different points along the strike, shows that there is a considerable variation, both in the number of beds of conglomerate and in the amount of quartzite between them. Individual beds have a lenticular character, swelling in places to a considerable thickness and tailing off in other places to a mere parting. In spite of this variation along the strike, the different members of the Main Reef series have received a nomenclature which for convenience is retained as far as possible throughout the Rand. The highest member is termed the South Reef, since its outcrop lies farthest to the south. Then follow in downward succession the Main Reef Leader, the Main Reef, and the North Reef. Both the South Reef and the Main Reef are in reality composed of a variable number of small seams of conglomerate, and it is only by grouping these that any semblance of continuity is maintained. The most individualized bed, at any rate for a considerable proportion of the mines, especially in the central portion of the Rand, is the Main Reef Leader. Usually it

*'Transvaal System' of the Geological Survey of the Transvaal.

[9] F. H. Hatch. 'The Extension of the Witwatersrand Beds Eastward under the Dolomite, etc,' Trans. Geol. Soc. S. A., Vol. VII, 1904, p. 57. Already the exploitation of this concealed part of the syncline has been commenced east of the Springs on the properties of the Geduld and of the Brakpan company.

is of small thickness, but has a comparatively high gold content; while a characteristic feature is a layer of large pebbles on the foot-wall. It is separated from the Main Reef by some 6 or 7 ft. of quartzite, which in places carries scattered pebbles and is then known as the Bastard Reef. From the South Reef it is separated by a bed of quartzite, varying in thickness from 35 to 100 ft. Similarly, the North Reef lies some 50 ft. below the Main Reef.

The sections following, from different parts of the Rand, will serve to illustrate the nature of the variation in number, thickness, and relative position of the beds. (Fig. 6, 7, and 8.)

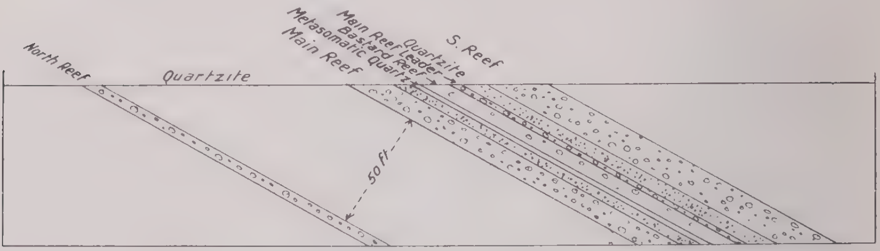

FIG. 6. SECTION OF MAIN REEF SERIES OF CONGLOMERATE IN THE KNIGHTS DEEP MINE, EAST RAND.

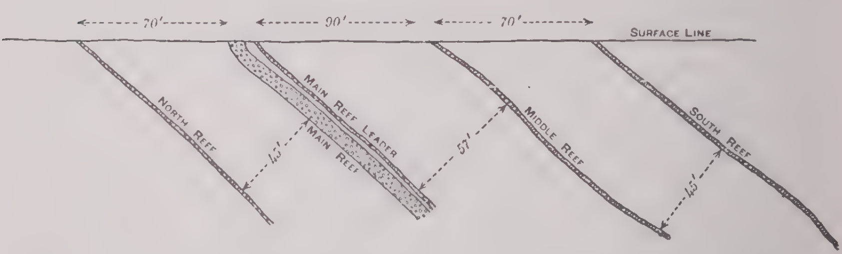

FIG. 7. SECTION OF MAIN REEF SERIES OF CONGLOMERATE IN THE ROBINSON MINE, CENTRAL RAND. (After Hatch & Chalmers.)

The Main Reef is characterized by its great thickness, its low gold content, the generally uniformly small size of its pebbles, and its large percentage of iron pyrite, which also carries more copper than the pyrites of the overlying conglomerates. The South Reef is generally separable into the foot-wall seam known as the South Reef Leader and the larger body of poorer conglomerate known as the South Reef.

In the Central Rand (the district nearest Johannesburg) the bulk of the gold is obtained from the Main Reef Leader and from the South Reef. In fact, in the early days of mining these orebodies were alone worked; but latterly, since the reduction of the operating cost, the large body of low-grade Main Reef has been systematically mined.

Toward the eastern end of the Rand the conglomerate beds become gradually thinner and fewer in number until, in the extreme east, for instance, on the property of the Geduld company, the whole Main Reef series is represented by a bed at the most 3 ft. thick and generally much smaller, which contains a few thin seams of gold-bearing conglomerate separated by bands of quartzite. In this part of the Rand, however, the Livingstone conglomerates, which occur some 400 to 500 ft. higher in the succession, have in

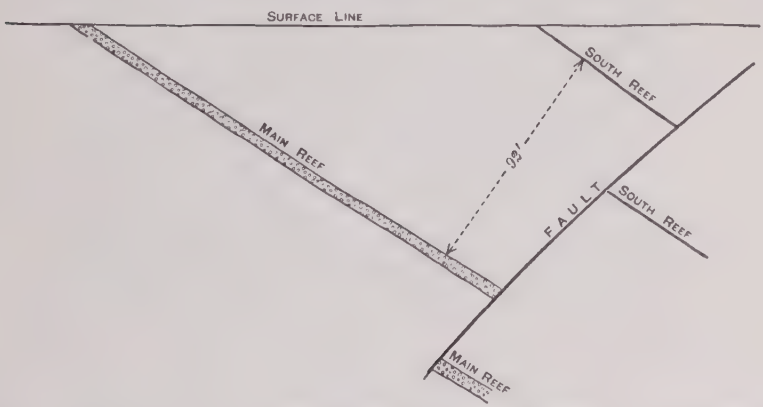

FIG. 8. SECTION OF MAIN REEF SERIES OF CONGLOMERATE IN THE DURBAN ROODEPOORT MINE, WEST RAND. (After Hatch & Chalmers.)

places a sufficient gold content to make it profitable to work them, as, for instance, on the Van Ryn property; and it may be mentioned, as bearing on the origin of the gold, that in places the Bird and Kimberley conglomerates have also been found to carry sufficient gold to invite the expenditure of considerable sums of money in ascertaining whether they could not be worked at a profit.

On account of their economic importance, a few details of the petrographical character of the conglomerates composing the Main Reef series are here given. They consist mainly of rolled fragments of quartz pebbles, but fragments of quartzite, banded chert, and slate also occur, these having a much more angular shape than the quartz pebbles. The pebbles, which are worn smooth and round by attrition and have been obviously water-borne, lie in a matrix that originally consisted of quartz sand, but which by the abundant deposition of infiltrated silica has been converted into a compact mass of quartz in which even the boundaries of the pebbles are difficult to distinguish on freshly fractured surfaces of the banket. Besides the quartz pebbles and the quartz sand, the only other constituents of the matrix that are undoubtedly original (that is, allogenic) are zircon[10] in microscopic crystals, and chro mite[11] and iridosmine[12] in rounded grains.

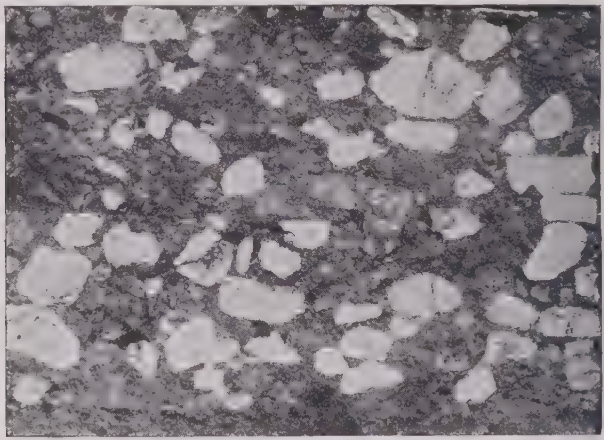

FIG. 9. WEATHERED SURFACE OF 'BANKET.' ¼ NATURAL SIZE.
(Photo by F. H. Hatch.)

The list of secondary (authigenic) minerals is much longer. The following have been observed: chloritoid,[10] chlorite, sericite,[10] calcite,[12] tourmaline,[10] rutile,[10] pyrite, marcasite, pyrrhotite,[11] chalcopyrite,[13] blende,[13] galena,[13] stibnite,[13] cobalt and nickel arsenides,[14] graphite,[10] gold telluride,[11] and gold.

Next in importance to the secondary quartz of the matrix, which has been responsible for widespread silification, is the iron pyrite, which, in like manner, has caused an extensive pyritization. It is present everywhere and in places abundant, on the average probably constituting 3% of the rock; and it is of great importance both from a scientific and economic aspect, owing to the fact that the gold is in intimate association with, and, as will be shown

[10] Hatch and Corstorphine. 'The Petrography of the Witwatersrand Conglomerates,' Trans. Geol. Soc. S. A., Vol. VII, 1904, p. 140.

[11] R. G. Young. Trans. Geol. Soc. S. A., Vol. X, 1907, and Vol. XII, 1909, pp. 82-100. 'Notes on the Auriferous Conglomerates.'

[12] Kuntz. Trans. Geol. Soc. S. A., Vol. VI, 1903, p. 74.

[13] Hatch and Chalmers. 'Gold Mines of the Rand,' London, 1905, p. 69.

[14] A. Crosse. Trans. Geol. Soc. S. A., Vol. XIII, 1910, p. 77.

later, in genetic relation to this mineral. This constituent possesses a markedly crystalline character, even occurring in almost perfect crystals, which present the faces of the cube, the octahedron, and the pentagonal dodecahedron. Occasionally, however, it takes the form of small spherules of the size of buckshot. These when broken show a radially fibrous structure, and some of them are made up of concentric layers. They are undoubtedly concretions, probably of the rhombic variety of marcasite. There are also rounded pieces of pyrite that show no concretionary structures and are so exactly like pebbles that they have been confidently asserted by some observers to be "rolled pebbles", of detrital origin similar to that of the quartz pebbles themselves. It is extremely probable, however, that these are pseudomorphs after quartz.

The crystalline character of the bulk of the pyrite and the fact that it not only moulds the allogenic constituents of the banket (for instance, the zircon), but also the authigenic chloritoid, proves that the introduction of this mineral took place at a period long subsequent to sedimentation. As to the so-called pebbles of pyrite, this would appear to be a case of metasomatism belonging to a still later (post-cementation) period; for C. R. Young has shown that both quartz pebbles and quartz cement have been replaced by pyrite. That metasomatic processes did play an important part in the post-cementation period of the history of the banket is shown by the fact that calcite has been found in all stages of replacement of quartz pebbles, and cement[15] and quartz is found replacing chloritoid.[16] Another authigenic constituent which, though rarely absent, is only relatively abundant in a few mines is a graphitic variety of carbon.[17] C. R. Young[18] has recently recorded observations which are quite opposed to this carbon having been derived from original organic matter deposited during sedimentation; since, according to him, it has in some places replaced the quartz of the banket, thus suggesting that it has been introduced at a late period in the history of the rock, by the vehicle of the magmatic vapors accompanying the intrusion of the abundant igneous dikes.

As to the gold, an examination of thin sections, under the microscope, discloses the existence of a close genetic relation between it and the pyrite; for the gold is seen to occur in angular subcrystalline particles attached to the periphery of individual crys-

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[15] Kuntz. Trans. Geol. Soc. S. A., Vol. VI, 1903, p. 74.
[16] Young. *Ibid*, Vol. X, 1907, p. 27.
[17] Hatch and Corstorphine. Trans. Geol. Soc. S. A., Vol. VII, 1904, p. 142.
[18] Trans. Geol. Soc. S. A., Vol. XIII, 1911, p. 65.

tals of pyrite.[19] It also occurs in the interstices between aggregates of pyrite crystals and in some cases particles of the noble metal are found completely surrounding spherular concretions of pyrite. Thus the so-called buckshot pyrite of the Rietfontein mine (already mentioned) is frequently found plastered with gold. When the graphitic carbon is present, there is also an intimate relation between it and the gold, which occurs thickly incrusted upon it. Gold is also found in the secondary quartz, cementing the cracks of broken quartz pebbles in the banket. It also occurs in the quartz veins that often seal fault-fractures, or are associated with the igneous dikes, which in most cases have also been intruded along fault-fractures.

There is a well known instance in the Ferreira mine[20] where a dike has been intruded between the foot-wall of the South Reef and the underlying quartzite. The actual foot-wall of the conglomerate is formed by a vein of metasomatic quartz, and both quartz and dike have a rich gold content. In these cases there appears to be direct genetic connection between the igneous intrusion and the gold. In other cases it has been observed that a dike often forms the division between a rich area and a poor area of a conglomerate bed, clearly indicating that the intrusion was at least not later than the precipitation of the gold.[21]

That gold has been precipitated in the banket at various periods in its history is clear; on the other hand, there is no case on record of a nugget or of a grain or flake of gold being found which bore on its surface any signs of detrital origin or in any way resembled alluvial gold. The conclusion can therefore scarcely be avoided that the gold owes its present position in the banket to precipitation at some period long subsequent to the sedimentation of the conglomerate. This is indeed admitted by those who, like G. F. Becker[22] and J. W. Gregory,[23] argue that the gold is of alluvial origin, by which they mean that it was first brought into the conglomerate by the agency that controlled its sedimentation, although subsequent solution and crystallization have obliterated any direct

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[19] C. R. Young describes (Trans. Geol. Soc. S. A., Vol. X, p. 26) a case where a fragment of gold obtained from the crushing of banket showed distinctly the striations of the cube faces of the pyrite crystals to which it had been attached.

[20] S. J. Truscott. 'The Witwatersrand Goldfields,' London, 1898, p. 112.

[21] Hatch and Chalmers. 'The Gold Mines of the Rand,' London, 1895, p. 71.

[22] G. F. Becker. Eighteenth Ann. Rep. U. S. Geol. Survey, 1896-97, V, p. 167.

[23] J. W. Gregory. Trans. Inst. Min. and Mèt., Vol. XVII, p. 41.

evidence of this. Becker sought to support his argument by reference to the pebble-like pieces of pyrite described above, which he claimed to be of detrital origin; and Gregory attached much importance to the supposed small vertical range of gold distribution in the conglomerate series. It has been shown above that it is probable that the pebble-like bodies are pseudomorphs after quartz pebbles and that the gold is by no means limited to a particular horizon, since it not only occurs in the various members of the Main Reef series—which themselves have a vertical range of several hundred feet—but also in the Livingstone, Bird, and Kimberley conglomerates, which together represent a vertical range of from 4000 to 5000 ft. Similar conditions of gold deposition are also found in the conglomerate at the base of the dolomite formation, which occurs at a horizon at least 12,000 ft. higher in the succession, and after an interval of time represented in addition by two considerable unconformities. The gold in these conglomerates (Black Reef) is of similar occurrence to that in the Main series, and in places the conglomerates have a gold content sufficiently high to render mining profitable.

Another theory advanced to explain the origin of the gold in the banket is that both gold and pyrite are chemical precipitates from the marine waters in which sedimentation took place. This theory was first formulated by Penning[24] in 1888. It received the support of O. Stelzner[25] in 1894, and, with some hesitation, of L. De Launay[26] in 1896. These authors compare the auriferous conglomerates, in this respect, to the copper-bearing slates (kupferschiefer) of Mansfeld, to the galena-bearing sandstone of Commern and Mechernich, and to the copper-bearing conglomerates of Boleo in Mexico; but the secondary origin by impregnation of the Mansfeld, Commern, and Mechernich ores seems now to be established.[27]

The chemical theory, certainly, has this advantage over the placer theory, that it does not postulate the destruction of such enormous quantities of auriferous quartz veins as would be required to explain the occurrence of gold in the conglomerate beds. But it has, equally with the placer theory, to surmount the difficulty of the repeated occurrences, after considerable intervals of time.

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24 Penning. Jour. Soc. of Arts, Vol. XXXVI, 1888.

25 Stelzner-Bergeart. 'Die Erzlagerstätten,' Vol. I, 1904, p. 384.

26 L. De Launay. 'Les mines d'or du Transvaal,' Paris, 1896, p. 299 *et seq.*

27 Beyschlag, Krusch and Vogt. 'Die Lagerstätten der Nutzbaren Mineralien,' Vol. I, 1909, p. 185.

Compare also 'The Ore Deposits of New Mexico,' by W. Lindgren, L. C. Graton, and H. C. Gordon, U. S. Geol. Survey, Prof. Paper 68, 1910.

of the peculiar conditions that could bring about the concentration and the precipitation of gold from sea-water during the accumulation of the littoral sediments. It does not appear probable that the assumed method of littoral gold deposition, either by mechanical or by chemical means, which, even if possible, could only be brought about by special conditions, should have been continued over such a long period of time and should have repeated itself after considerable geological intervals. The origin of the gold in the Witwatersrand banket has been referred to as one of the greatest riddles of modern times, but evidence is slowly accumulating to prove that the Rand banket is not a fossil 'placer' but rather that its gold content has an origin similar to that of quartz veins.

If on the basis of the ascertained facts, detailed in the foregoing pages, an attempt is made to summarize the geological history of the Rand banket, the multiplicity and complicated character of the metamorphic processes involved become apparent. The following stages can, however, be established with some degree of certainty:

(1) The classification and sedimentation of the coarse and fine material derived by denudation from the land surfaces of the ancient Swaziland formation.

(2) The consolidation, under a growing cover of fresh sediments, of the loosely aggregated pebble and sand beds to conglomerates and quartzites by cementation with silica (quartz).

(3) The burying to a great depth of the earlier sediments under later accumulations. The development of chloritoid from argillaceous material in the sediment probably took place during this period.

(4) (a) The elevation of the beds, accompanied by folding and fracturing.

(b) The filling of the fractures thus formed by the injection of igneous material, the process being accompanied and followed by pyritization, the deposition of carbon, and the precipitation of gold from the warm magmatic waters given off during the solidification of the igneous intrusions.

The development of sericite, probably at the expense of some allogenic felspathic constituent of the banket and the replacement of the pyroxene of the earliest basic dikes by chlorite, were no doubt due to the influence of the compensatory differential movement that accompanied and followed this period of elevation.

(5) The metasomatic replacement of both allogenic and authigenic quartz by pyrite and by calcite, as well as of chloritoid by quartz, and the sealing of small fractures by quartz; all these processes being accompanied by a renewed precipitation of gold.

(6) The destruction of the pyrite within the zone of weathering by oxidation and consequent liberation of its mechanically included gold, followed by the concentration of the latter by secondary enrichment.

REPLACEMENT OREBODIES.

Their Characteristics and the Criteria by Means of Which They May be Recognized.

By J. D. Irving.

Introduction.

HISTORICAL REVIEW.

Of recent years ideas concerning many phases of the formation of deposits of the ores of the metals have made rapid advances and the processes involved in their formation have been made clearer by careful investigation and study. In this way it has come to be clearly understood that the most fundamental distinction in the larger grouping of metalliferous deposits is that between those which have been formed contemporaneously with the enclosing rock and thus are part and parcel of it, owing their origin to the same set of processes which have produced the rock itself, and those which have in some way been introduced into the country rock after (and generally long after) its solidification in the form in which we know it. To the first group the term 'syngenetic' has been applied, to the second, 'epigenetic,' words which may be translated into simpler language as *contemporaneous* and *subsequent*. With the second, or epigenetic group, this discussion is entirely concerned.

In epigenetic deposits the constituent minerals are known beyond question to have found their way to the places where they are now found, since the enclosing rock has assumed its present condition. If an eruptive, as granite, it was a granite in all essentials as it now exists before any mineral deposit was formed in it. If a sediment, it was an already consolidated rock, be it limestone, sandstone, shale, or other sediment, before it was invaded by the agents which formed the ores now found in it. In order to find a resting place in solid rock masses, metalliferous ores must in some way gain an entry into the rock. Either the space which they now fill must have been ready for their entry at the time of deposit, or the rock material must have been in some way expelled to make room for them. F. Posepny[1] has expressed this self-evident fact most admirably: "With relation to the xenogenites (*i.e.*, epigenetic), or mineral deposits, the first question concerns the space which every secondary mineral or mineral-aggregate requires to establish its existence. It must either have found this space waiting for it, or it must have made room by driving out an original mineral."

In the earlier years of the study of ore deposits the space was generally considered to have first existed in the rock, forming a receptacle in which the deposition of foreign mineral substance could go on. That fissure veins were long tacitly regarded as the prevailing type of epigenetic deposits, did much to strengthen this view. Deposits now believed not to be cavity fillings were little understood and attempts to explain them always found expression in terms of cavity fillings. The classification of ore deposits depended largely on the form of the cavity which received the deposit. When disseminated particles of mineral foreign to the country rock were found in rocks adjoining fissures, or in large disseminated masses about little cracks, they were called 'impregnations' and were regarded as pore spaces in the rock which had been invaded and filled with ore which had migrated to limited distances from the conduit. No account was taken of the fact now known, that the porosity of some rocks in which such impregnations are found, is less than the volume of the minerals introduced into the rock; as, for instance, the granites adjoining the tin veins of Cornwall, where such deposits are called 'carbonas.' Again, great irregular masses, wholly enclosed in limestone, such as those at Leadville, Colorado, Eureka, Nevada, and elsewhere, which were evidently epigenetic in character, but had not found simple fissures for a resting place, were explained as filling spaces of dissolution; that is, as caverns in the limestone which had been dissolved out by percolating waters, caverns which had their analogues in the Mammoth and Wyandotte caves in Kentucky and Indiana. The words of Arnold Hague as late as 1891[2] relating to the great irregular deposits of Eureka, Nevada, are interesting in this respect: "A study of these channels and their intricate connections tends to the belief in the theory of pre-existing caves and underground water

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[1]'Genesis of Ore Deposits,' Trans. Amer. Inst. Min. Eng., Vol. XXIII, p. 207.

[2]Hague, Arnold. 'Geology of the Eureka District, Nevada,' Mon. XX, U. S. Geol. Surv., 1892, pp. 308, 311, 316.

courses before the introduction of ore * * * it is most difficult to see how such vast accumulations of these sulphides could have been formed in any other way than in the pre-existing caves and openings. Any theory, with which we are acquainted, of chemical and physical replacement of the limestone or dolomite seems wholly inadequate to meet the necessary conditions. Pseudomorphs of galena and pyrite after calcite have been described as mineralogical curiosities and possibilities, but nowhere have they been found in large quantities in any mine, and so far as I am aware they have never been recognized at Eureka. * * * They (i. e., the ores) were for the most part deposited as sulphides in pre-existing caves and cavities.'' J. S. Newberry, writing in 1880, says: ''The Leadville orebodies were undoubtedly accumulated in vacant spaces formed by the solution of limestone.''[3]

At this stage, the idea which had suggested itself long before with relation to the silicious casts of fossils, silicified wood, etc., began to be applied to the formation of ore deposits. It had been recognized by mineralogists for many years that crystals of one substance could be altered chemically into a mineral of wholly different chemical composition and still retain the form of the original mineral. Such crystals were called 'pseudomorphs,' and certain of them could be shown to have resulted, not from a solution of the first mineral and a refilling of the space with the secondary mineral, but by a gradual molecular substitution of one substance for another. W. Lindgren[4] has cited the various classifications of pseudomorphs proposed so that at this point they need not be repeated. From its application in the case of a single mineral the process of molecular substitution was then applied by geologists and paleontologists to fossils composed of separate mineral grains. The pseudomorphism in this case was a retention of the form and internal structure of the fossil rather than of its individual crystalline grains, though the passage from a single crystal to an aggregate of crystals was simple and involved no new supposition. Archibald Geikie, writing in 1882, gave an admirable statement of the process as applied to fossils.[5] The application of this process to orebodies did not, however, proceed as rapidly. S. F. Emmons has shown[6] that Charpentier had distinctly formulated the theory of replacement as early as 1778, but

[3]'On the Origin and Classification of Ore Deposits,' *School of Mines Quart.*, 1880.

[4]Trans. Amer. Inst. Min. Eng., Vol. XXX, pp. 581-584.

[5]Text-book of Geology, 1st ed., 1882, p. 610.

[6]Emmons, S. F. 'Theories of Ore-Deposition Historically Considered,' *Eng. & Min. Jour.*, Vol. 77, p. 119.

that, like many opinions expressed without evidence, this remained unnoticed and was disregarded for many years. R. Pumpelly was the first to apply it in the United States to the copper deposits of Lake Superior in 1873. In 1886 it was applied by Emmons to the ore deposits of Leadville, Colorado. In 1887-8 it was applied by R. D. Irving and C. R. Van Hise to the formation of the iron ores of Lake Superior region in the Penokee Gogebic range. Surface waters were here described as descending until contact with impervious beds caused their accumulation and stagnation and ore was formed by substitution of iron oxide for county rock. In all of these cases it was asserted that no open space had ever existed other than that necessary to permit waters to gain access to the rock affected; that orebodies grew in rocks by the gradual replacement of the material by the new substance taking its place. An interchange of metallic sulphide or gangue mineral for country rock was supposed to have occurred. The process was considered chemical, and in a measure akin to the replacement of one crystal by another with retention of the form of the original, known under the general name 'pseudomorphism.' The process was correlated with pseudomorphism only in a vague way, and was variously termed *replacement*, *substitution*, *metasomatism*, or *metasomatic interchange*.

Once formulated, and here and there the process definitely proved to have taken place, the idea gained ground rapidly. Before 1900 it was applied to the formation of many ore deposits in limestone and also in many other types of rocks. Like nearly every new idea which explains natural phenomena not previously understood, origin by replacement has been eagerly applied to a vast number of deposits, some of which probably have had such an origin and some of which undoubtedly have not, as subsequent careful investigation has proved. The pendulum of thought indeed at one time swung so far to the side of replacement that some geologists questioned whether banded fissure veins might not have been in nearly all cases formed almost entirely by replacement.[7] A more conservative attitude of mind has now followed, and the theory of replacement as an ore-building process is applied with more care to only those orebodies to which no simpler explanation is applicable.

Until 1900 no attempt was made to definitely formulate any correlation between metasomatic processes of ore formation and pseudomorphism, or to present the subject in any single paper deal-

[7]Emmons, S. F. Trans. Amer. Inst. Min. Eng., Vol. XV, p. 123.

ing with the process in general. In that year, however (1900), Waldemar Lindgren published a paper in the Transactions of the American Institute of Mining Engineers, entitled 'Metasomatic Processes in Fissure Veins.'[8] In this essay the chemical and physical natures of the processes involved in the alteration of vein walls are discussed with such clearness and precision that economic geology owes to him for this masterly treatment a debt of gratitude which cannot be overestimated. It will seem to those who have studied this paper that there is little to be added to what Lindgren has so clearly presented. In many respects this is true, and I shall have occasion to refer frequently to his work; but it must be remembered that his paper deals chiefly with fissure veins in which metasomatic processes have formed orebodies that are essentially subordinate in importance to the fillings of cavities through which the replacing solutions have circulated. He was also especially concerned with the mineral changes of vein walls; that is, his paper was chiefly mineralogical and chemical. It is not my purpose to enter into such a detailed discussion of the chemical problems of replacement, but rather to describe some of the characteristic features of replacement deposits and to attempt to establish some criteria by means of which the effects of replacement may be recognized. I will also be concerned chiefly with those ore deposits in which replacement has been the preponderant process and cavity filling has been only subordinate. As such deposits are more common and larger in limestone formations than elsewhere, this paper will deal more largely with them than with other types. It may be urged as an additional warrant for a presentation of certain phases of this important subject that some criticism has recently been urged against it. One or two geologists believe, for instance, that it is often, if not nearly always, applied when an appeal to it is not only unnecessary but misleading.

Forms and Dimensions of Replacement Orebodies.

GENERAL.

Ore masses formed by replacement are characterized by great variations in size and a bewildering variety of form. As they are independent of open space available for free deposition, the size which they may attain is subject to no definite limits. They range from narrow mineralized borders forming penumbral margins around the edges of filled rock cavities to huge masses which equal or

[8] Trans. Amer. Inst. Min. Eng., Vol. XXX, p. 578-692.

exceed in their dimensions nearly all other types of ore deposits. Those which are formed by the replacement of massive limestones are especially apt to attain great size, presumably on account of the facility with which the process goes on in this especially soluble rock. Although their great irregularity precludes any very exact estimation of volume, the following table, giving the approximate maximum dimensions of some of the well known occurrences, will serve to convey some idea of the magnitude of some of the ore masses formed in this way.

SIZE OF REPLACEMENT DEPOSITS.

	Maximum Length, Feet.	Maximum Width, Feet.	Maximum Thickness, Feet.
Henriette-Wolftone-R. A. M. shoot, Leadville (oxides and sulphides)	3500	1600	200
Moyer main shoot (sulphides), Leadville	2340	1300	150
Gold ore-shoot (oxidized ore), Leadville	3000	400	240
Greenback shoot (sulphides), Leadville	350	500	300
[9]Eureka Nevada	400	150	100
COPPER QUEEN OREBODIES.			
I	600	250	150
II	600	830	100
III	500	225	150

The first impression gained from a comparative study of the collected plans and sections of replacement orebodies is that of great variety and extreme irregularity of form. A series of typical sections from Leadville, Eureka, Bisbee, and the Black Hills shows the extremely intricate and complicated shapes which these masses frequently assume. A more careful study, however, both of published figures and of actual occurrences in the field, serves to show that nearly all of these intricacies of form are referable to some well defined cause or causes, and that the complex shapes are not in any sense fortuitous. The causes producing these features are so simple that their statement seems hardly necessary, but that the general discussion of the subject may be clearer to those who have not had opportunity to observe this class of orebodies they are here separately stated. The shape of a replacement ore-mass is due to the following causes: (1) Relation to channels of access of ore-bearing solutions; (2) variations in chemical character and structural arrangement of enclosing rocks; (3) manner in which mineralizing waters have affected the rock; (4) amount of material supplied in solution.

[9]The Eureka orebodies are so extremely irregular that any exact measurements are impossible. These dimensions are measured on the '800 orebody,' U. S. Geol. Surv., Mon. VII, Plate III.

RELATION OF ORE-BEARING SOLUTIONS TO CHANNELS OF ACCESS.

The most important factor influencing the form of an ore-mass formed by replacement is the channel or opening which has admitted the ore-bearing solutions to the rock-mass which has been replaced. No substitution of ore for country rock can, of course, occur unless solutions have first been able to reach the rock susceptible to replacement.[10] The openings which occur in rocks are of many different kinds, and it is possible for replacement to be initiated from any of them irrespective of form or origin; joint-cracks, fissures, large faults, brecciated zones, horizontal spaces between separated strata, vesicular cavities, and intergranular spaces serve equally well as starting points for the process. All of these forms of rock opening undoubtedly serve as initial points for replacement; but those which are of comparatively small size and are discontinuous have simply permitted the extension and easy penetration and mineralization of a susceptible rock-mass, and cannot be regarded as the conduits or main channels of access. To serve as adits or connections between susceptible rock-masses and deeper seated sources of mineralizing waters, cavities must be continuous for considerable distances. They must be 'trunk channels' of some kind. That a susceptible rock should be porous, open textured, brecciated, or jointed, is an aid to mineralizers once they have reached the rock affected, but is insufficient in itself to afford access to mineralizers. It therefore happens that replacement orebodies are generally found associated with some form of fissures in the country rock which are either singly or collectively capable of conducting solutions from considerable distances to the locus of deposition. There are few, if any, instances with which I am familiar that do not permit either the actual observation of these fissures or their inference from the form and distribution of the ore masses. In the silicious gold ore-shoots of the Black Hills, South Dakota, they can be actually observed in the shale roof of the orebodies, sometimes as single fractures, sometimes as sheeted zones (see Fig. 1), sometimes as broad zones of intersecting fracture. In Leadville they are observable in some cases extending downward from the orebodies into the granite underlying the susceptible rocks as fissure veins of considerable width, or they may be inferred from the regularity of trend of the

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[10]Exception is to be made in the case of contact metamorphic ore deposits when orebodies develop in the neighborhood of intrusive igneous masses which have themselves yielded the solutions for the mineralization of the adjacent rock. Such deposits may form without the pre-existence of cavities.

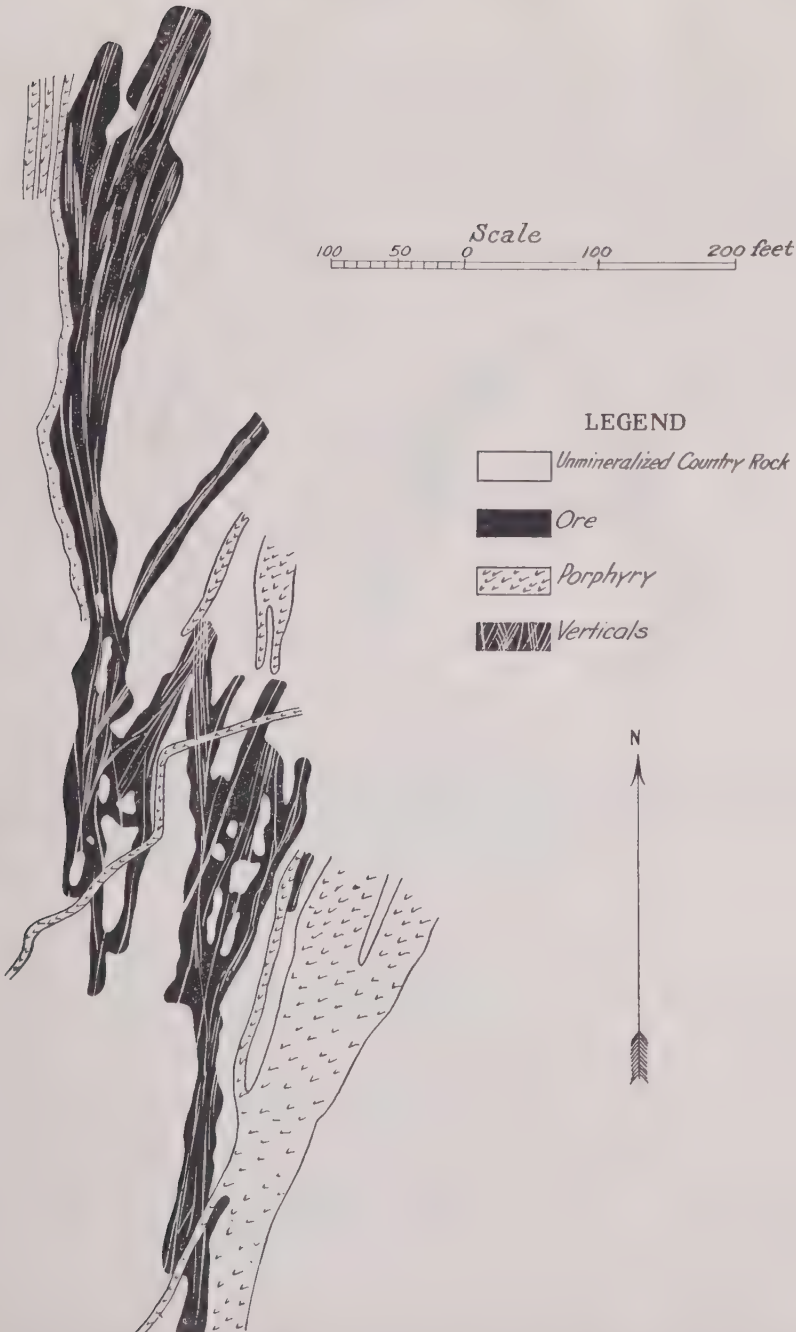


FIG. 1.
Plan of a portion of the Welcome mine, Black Hills, South Dakota, showing a flat orebody of considerable horizontal extent formed by the combined action of solutions rising through a number of closely spaced fissures.

shoots when plotted on a map. (See Fig. 6, 'Iron Hill Shoots.') The absence of fissures beneath many of the large orebodies of this region is probably due to the facility with which limestone rocks become re-cemented after rupture. In the case of fissure veins with limited amount of replacement along the walls, the channel of access is so very much more prominent than the replacement mass arising from it that there is no possibility of doubt as to the opening from which the mineralization started.

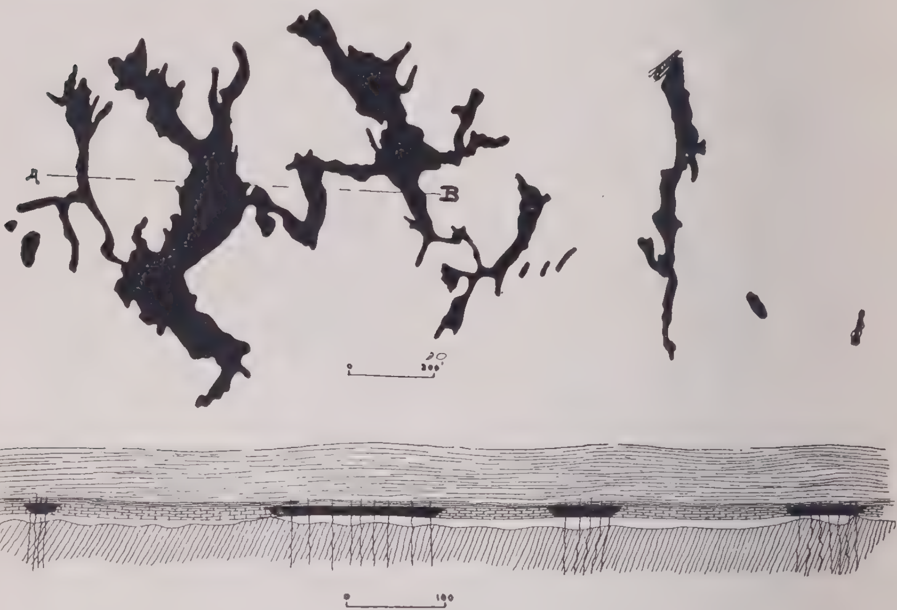


FIG. 2.

Plan (A) and part section (B) of the ore-shoot of the Penobscot mine, Garden City, Black Hills, South Dakota, showing the relation of the form of the orebodies to 'channels of access' and manner in which small offshoots form on single fractures which run out into the rock from the main fractured zones.

When solutions have once gained access to rocks susceptible to replacement, joint-cracks, rock pores, brecciated structures, stockworks, and other smaller and less continuous openings, by affording easy circulation and increasing the available surface for chemical action, greatly facilitate and accelerate the process.

FORMS DUE TO SINGLE FISSURES.

Where replacement has proceeded from a single fissure intersecting a homogeneous rock the form of the resulting replacement mass usually is tabular. Its boundary will sometimes be extremely indefinite, the new minerals becoming more and more sparsely scattered outward from the conduit which admitted the solution until the ore passes insensibly into country rock (Fig. 3, B). At other times it will be extremely sharp so that the passage from ore to country rock is abrupt (Fig. 3, A). In all cases, however, the boundary, though as a whole tabular, will rarely be parallel in detail to the wall of the channel of admission, and irregular apophyses will run outward from the main replacement mass, where solutions have for some reason operated more extensively than in other places. In

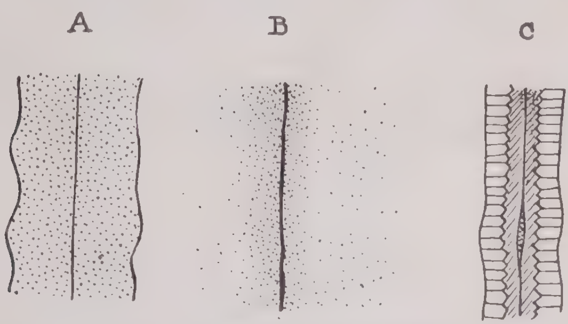


FIG. 3. DIAGRAMATIC SKETCHES.

A shows how replacement which arises from a single fissure is sometimes sharply separated from the mineralized rock. B. The same relation to a fissure but fading gradually into the country. C. Filled fissure with no replacement.

some cases, as at East Huell Lovell, Cornwall, England, the rock along some one portion of an opening has been more extensively attacked than at others. A lenticular mass is then produced.

It is often difficult to determine, where fissures intersect homogeneous rock masses, why some portions of the wall rock have been extensively attacked and others scarcely at all; but this is frequently true. Possibly a slightly greater porosity, or the absence of intervening layers of impermeable selvage clay or a slight difference in the composition of the original rock may have determined it, or the constriction of the fissure above the most extensive replacement mass may have permitted the stoppage and stagnation of the solutions and afforded them more time in which to effect an interchange of new for old minerals. In some cases such replacements are asymmetrical laterally and a selvage clay on one side has prevented replacement, so that the rock on the other only has been attacked.

The distance to which replacement may extend from a single channel varies greatly. In compact rocks like granite it is usually small, perhaps not over 4 or 5 ft. Again in the Cambrian limestone in the Black Hills, the distance though greater is still not very great; possibly not over 10 to 15 ft. In the more permeable limestone in the Neodesha mine near Ouray it extends for more than 100 ft. Such an extent from a single fissure is exceptional; especially where the fissure is in homogeneous rock, all portions of which are equally susceptible to replacement. When viewed in plan shoots arising from single fissures are seen to have a roughly lenticular form, the widest portion being at that point where the supply of mineralizing water was present in greatest amount.

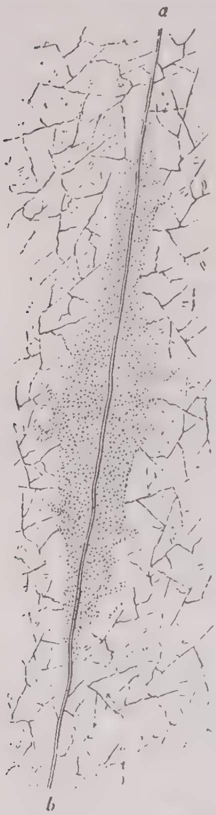


FIG. 4. (After Phillips.)

Horizontal section of carbona on the 100-ft. level of East Huell Lovell, Cornwall. Width at the widest point, 9 ft. Shows how rock along one portion of channel of access is extensively replaced and elsewhere slightly.

FORMS DUE TO MULTIPLE FISSURING.

If all fissures were widely spaced single openings, it is probable that replacement masses would show little variety of form other than that which will be later described as due to the chemical composition and structural arrangement of the rocks intersected by the opening. Fissures are, however, notably variable in their position and relation to one another. They rarely occur alone, but rather in parallel or intersecting groups or systems. Where more than one fissure or opening occurs nearer to another than the distance to which replacement may proceed, the replacement mass arising from one coalesces with that proceeding in the opposite direction from the next adjoining and a large mass of ore is thus produced. It is then obvious that the larger features of the form of a replacement mass, that is, the form as a whole, in a homogeneous rock will be determined by the distribution and spacing of the openings. If viewed in section and plan, fissures may be arranged (1) in parallel groups, (2) in intersecting groups.

Parallel Groups; Lode Fissures.—Parallel fissures accompanied by extensive replacement give rise to what may be conveniently termed 'lode fissures.'[11] Where rocks have been fissured and faulted it often, indeed generally, happens that the opening is not a single fissure. The movement is distributed along a series of parallel, closely spaced fissures, usually of very small width, which include between themselves narrow tabular plates of country rock. These fissures are most frequently closely spaced along the centre of the zone, the plane of maximum movement, but separated by wider and wider plates of country rock in either direction. Such groups of parallel fissures are generally termed 'sheeted zones'. Solutions entering a sheeted zone often replace the narrower plates completely and result in a solid tabular mass of ore in which the traces of the original fissuring produce a banded structure not unlike that caused by true crustification. Fig. 5 below illustrates

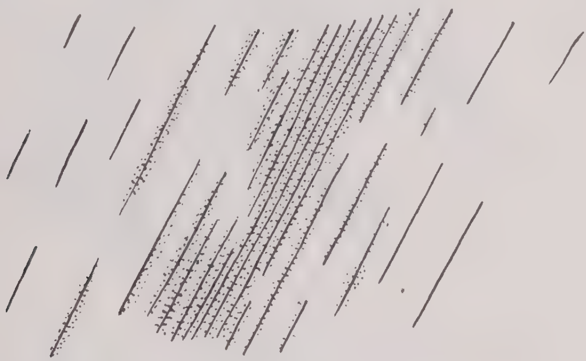


FIG. 5.

Lode fissure formed by the replacement of plates of rock in between multitudes of parallel fractures. Fissures decrease in number from centre of disturbance outward.

a fissure of this kind. It sometimes happens that in lode fissures of this kind the central portion only of the lode is a solid mass of ore. Beyond this central zone the individual fractures are separated too widely to allow the mineralization arising from adjacent fissures to coalesce. The main lode is thus often separated by a plate or wall of barren rock from narrower parallel side lodes, and important and commercially valuable veins are not infrequently overlooked owing to a failure to understand the origin of the vein. In

[11]These are termed by S. F. Emmons, 'replacement veins.' See text accompanying Butte Special Folio, U. S. Geol. Surv., Folio No. 38.

horizontal projection lode fissures of this kind differ little, if at all, from normal fissure veins, into which, indeed, they pass by imperceptible gradations when the open space increases in amount and the replacement walls extend to less distance into the adjacent rock.

Intersecting Groups.—Intersecting fissures divide the rock masses which they intersect, into groups of polygonal angular blocks (Fig. 37). The form of replacement bodies arising from such systems depends chiefly upon the closeness of the spacing. If the fissures are wide apart, the polygonal blocks of country rock which inter-

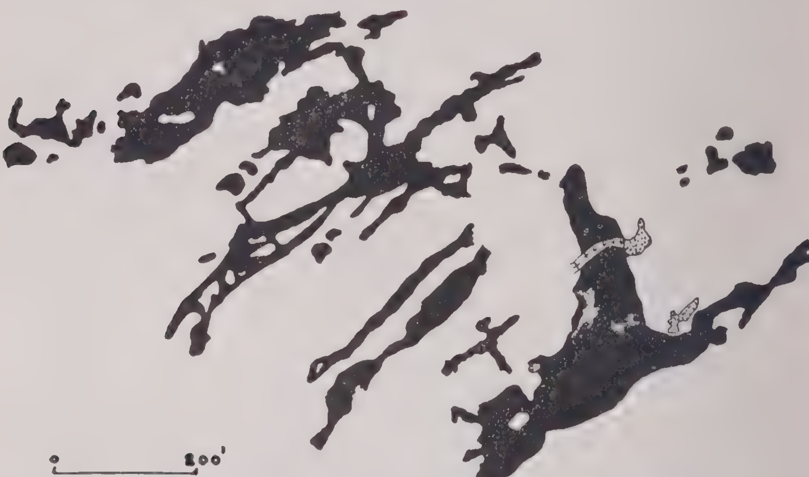


FIG. 6.

Plan of ore-shoots on Iron hill, Leadville, Colorado. (After A. A. Blow. Corrections and additions made by Irving. Shows great size of shoots, irregularity of outline in detail, and evidence of formation along zones of fissuring. (North is toward the left in the map.)

vene are larger than the width of the replacement body arising from any single fissure, and a series of replacement orebodies results both in plan and section, which is no more than a group of single fissure replacement shoots intersecting one another. Fig. 6 and 7, illustrate this. The intersections of such shoots are rarely angular, for the solutions round off the narrow points between the intersections and often produce a larger and more irregular mass than along that part of the fracture which is further removed from the point of intersection. When fissures are more closely spaced so as to form stockworks they are often nearer together than the distance to which replacement arising from a single fissure may readily extend, and the entire rock mass is replaced with its outer limits determined by the limits of the fractured portion of the country rock. As movements which result in the rupture of rocks generally occur along lines or linear zones whose longer diameter is much greater than the distance across the fractured zones, such ore deposits are generally linear. The presence of stockwork-like fissures can be readily detected in such masses at their edges, as there the fractures become fewer in number and run out into the unmineralized rock. The replacement shoots arising from them also run out into the country, forming a peculiar fringe of little

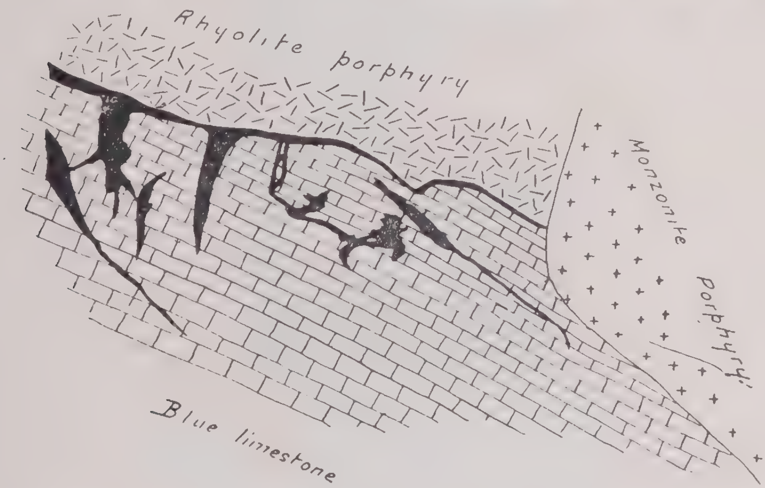


FIG. 7.

Cross-section of the ore-shoots of the Oro La Plata mine, Leadville, Colorado, showing the extremely irregular character of the ore-shoots formed along irregular fractures in the blue limestone.

offshoots or apophyses which by their parallel arrangement disclose the presence of the fissure systems which have given rise to them. In massive rock, like heavy bedded limestone, the fracturing of the rock is often so irregular that the polygonal blocks which intervene between individual joints have very complicated forms and the resulting ore masses are characterized by the most extraordinary and intricate form. Fig. 7 illustrates this. When multiple intersecting systems of closely spaced minute fissures intersect rocks which are chemically more resistant than limestone, as in the Treadwell mine in Alaska, the replacement extends to only very short distances from any single fissure, and yet the resulting mass through which the ore is disseminated is of great size

Minor Irregularities of Outline.—In addition to the larger features of form which are more or less directly referable to the distribution and arrangement of fissures, there are many detailed irregularities of form which are independent of the direction and position of the fissures from which waters have operated. When solutions migrate outward from a fracture they replace the rock to varying distances so that the surfaces of demarcation between the outside edge of the ore mass and the unaltered country rock are rarely, if ever, parallel in detail to the opening from which the solutions originated, but are curved and wavy surfaces. While these surfaces are in some cases roughly parallel to the fissure and

FIG. 8.

Galena replacing limestone from Leadville, Colorado, showing wavy line of demarcation between galena (black) and limestone (white). About ½ natural size.

only irregular in their more minute details, in others they extend out in 'pipes' or apophyses which wander without regularity of direction for often considerable distances beyond the main body of the ore and form a mass whose outlines are frequently bewilderingly complex. Between these two extremes all gradations occur. Fig. 8, 9, and 10 illustrate this irregularity, which is often noticeable in the detail of the lines of demarcation between ore and rock. In these specimens the boundaries are sharp and do not, as is often the case, fade off gradually into the surrounding rock.

In some cases long pipe-like arms, roughly circular in cross-section, wander outward, twisting and turning as they go for sometimes as much as 30 or 40 ft. away from the main mass and apparently independent of any perceptible opening. One of these is shown in Fig. 10. Apophyses of this kind are often difficult to explain. They are probably due to differing porosity in the areas replaced; but no comparison can be made of the rock replaced with that unaffected, as it has now been altered to ore. Care must be

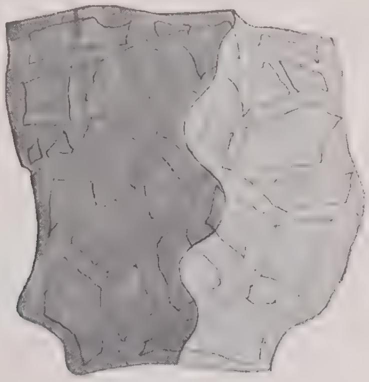


FIG. 9.

Wavy line of direction between ore (dark) and limestone (light) from silicious ore on Dacy Flat, Ragged Top, Black Hills, South Dakota. The general direction of the supplying fissure is about parallel to the right-hand edge of the specimen. About ¼ natural size.

FIG. 10.

Specimen of silicious ore from Penobscot mine, Black Hills, South Dakota. Shows wavy line of demarcation between ore (dark) and limestone (light). About ½ natural size. The dark spaces in the ore are cavities due to decreased volume.

taken not to confuse irregular arms and apophyses of ore of this kind which are independent of any auxiliary fissure with 'pipes' of ore such as those in the Yankee Boy and Guston mines[12] near Silverton, Colorado. The latter seem to have been formed along what Schwartz terms 'ore breaks', that is, channels of minimum friction along intersections of sheeted zones or fissure systems.

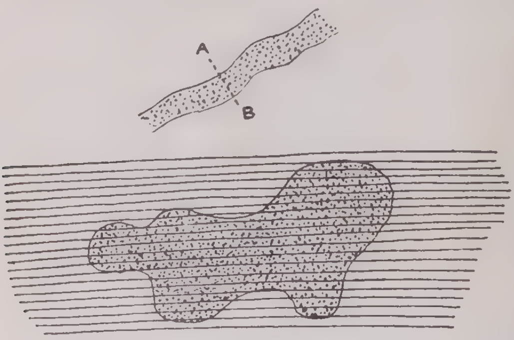


FIG. 11.

Plan and cross-section of long irregular arm of ore which makes out from the main body into the stratified limestone and preserves the sedimentary banding of the limestone in the ore. Scale of section 10 times that of plan. Portland mine, Portland, South Dakota.

The apophyses here described are merely irregularities in detail of the 'free faces' of masses which are in general easily referable to some fissure in the country rock and are rarely of large dimensions unless some auxiliary fissure or opening in the rock has determined their form and extent. Fig. 12 shows both classes of detail at the edges of a single orebody.

VARIATIONS IN CHEMICAL CHARACTER AND STRUCTURAL ARRANGEMENT OF ENCLOSING ROCKS.

Fully as important in determining the shape of replacement masses are the chemical character and structural arrangement of the enclosing rocks. Fissures do not occur exclusively in homogeneous rocks, or in rocks composed of grains of one mineral only. They frequently pass through rocks of widely varying lithologic character or rocks that, although as a whole homogeneous, are made up of aggregates of different minerals which have widely different susceptibilities to replacement processes.

[12] Schwartz, T. E. Trans. Amer. Inst. Min. Eng., Vol. 26, p. 1056.

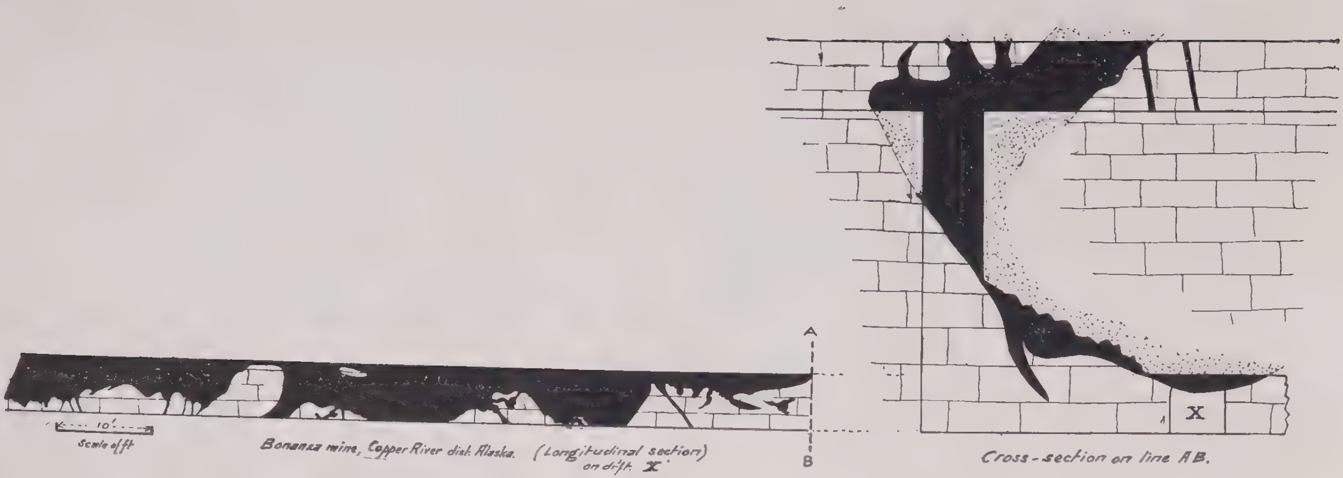


FIG. 12.

Plan and section of tunnel and winze in Bonanza mine, Chitina River copper district, Alaska. Shows a large body of almost solid chalcocite replacing limestone. The irregularity in detail and the relation 'in part' of this irregularity to fissures is indicated very clearly in this section. Scale of both sections is the same.

FORMS PRODUCED IN ROCKS COMPOSED OF DIFFERENT MINERALS.

When rocks are mechanical mixtures of different minerals, some minerals will be more resistant to chemical alteration or replacement than others. Thus, in a calcareous sandstone composed of grains of sand cemented together by calcite, the calcite will be readily replaced; but the more resistant quartz will be left without alteration. In a granite that is composed of feldspar, muscovite, and quartz, the feldspar may suffer replacement while the quartz and mica remain unaffected. It therefore happens that rocks of this kind when affected by any given solution will often be but partly replaced and that the ore resulting from the process will be disseminated through the mass in much the same attitude as the original susceptible mineral. A calcareous quartzite of this kind has been transformed into ore in some of the Black Hills silicious-ore districts, only the cementing calcite having yielded to mineralizing processes. This disseminated type of replacement deposit where only the favorable minerals of the rock have been replaced is especially common in the case of igneous rocks. The edges of such masses are rarely sharp, but almost always fade gradually into country rock and rarely, if ever, present the abrupt boundaries which are so often found in rocks which are replaceable as a whole.

FORMS PRODUCED BY VARIATION IN STRUCTURAL ARRANGEMENT OF ROCKS.

When fissure channels of access pass through rocks of differing susceptibility, the more susceptible rocks are usually replaced to greater distance than the unsusceptible, and the resulting form is then tooth-shaped and depends upon the shape and extent of the susceptible layer more than upon the direction and position of the fissures. This is especially noticeable where fissures intersect alternating layers of sedimentary rocks of different chemical composition, such as limestone, shale, and quartzite. The limestone will usually be extensively replaced and the other rock layers only slightly. If only one especially susceptible layer is present and is of limited thickness, it is frequently replaced completely from underlying to overlying insoluble layer. The result is a bedded deposit with irregular boundaries only where the end of the replacement mass crosses the replaced bed. Elsewhere it is evenly and often conformably bounded by the adjacent insoluble strata. In plan the forms of bedded masses such as this, are determined by the fissures or fissured zones along which they extend. An excellent illustration is that given in Fig. 2, where the bedded form due to the position and thickness of the original limestone layer is admirably seen in cross-section, and the irregular outlines and evidence of intersecting fissure systems are seen in the plan. Another illustration where the fissure is relatively wide and the replacement bed extends only for a short distance away from the fissure, is shown in Fig. 13.

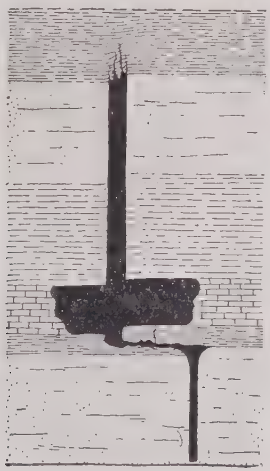


FIG. 13.

Cross-section of vein near Ouray, Colorado. Shows a fairly wide fissure vein intercepting a limestone bed with replacement shoot formed in the limestone and extending to 15 or 20 feet from the fissure on either side of the main vein. (After J. D. Irving, Bull. 260, U. S. Geol. Survey.)

If the replacement mass is smaller than the susceptible rock mass which lies between the impervious bounding rocks, there will be a line of demarcation between it and the unreplaced portion of the susceptible rock which will have the usual wavy outline or will show gradual transition into country rock. For the sake of convenience this may be called the 'free face.' Fig. 14, 15, 16, and 17 show plans and sections of the ore-shoots from the Black Hills of South Dakota which illustrate the same feature.

It is easy to see why such masses as that shown in Fig. 16 were confused by early writers with sedimentary layers and why they are still included by many writers among the 'bedded deposits' where the old classification by form is still in use. It would be exceedingly interesting to learn whether the much-dis-

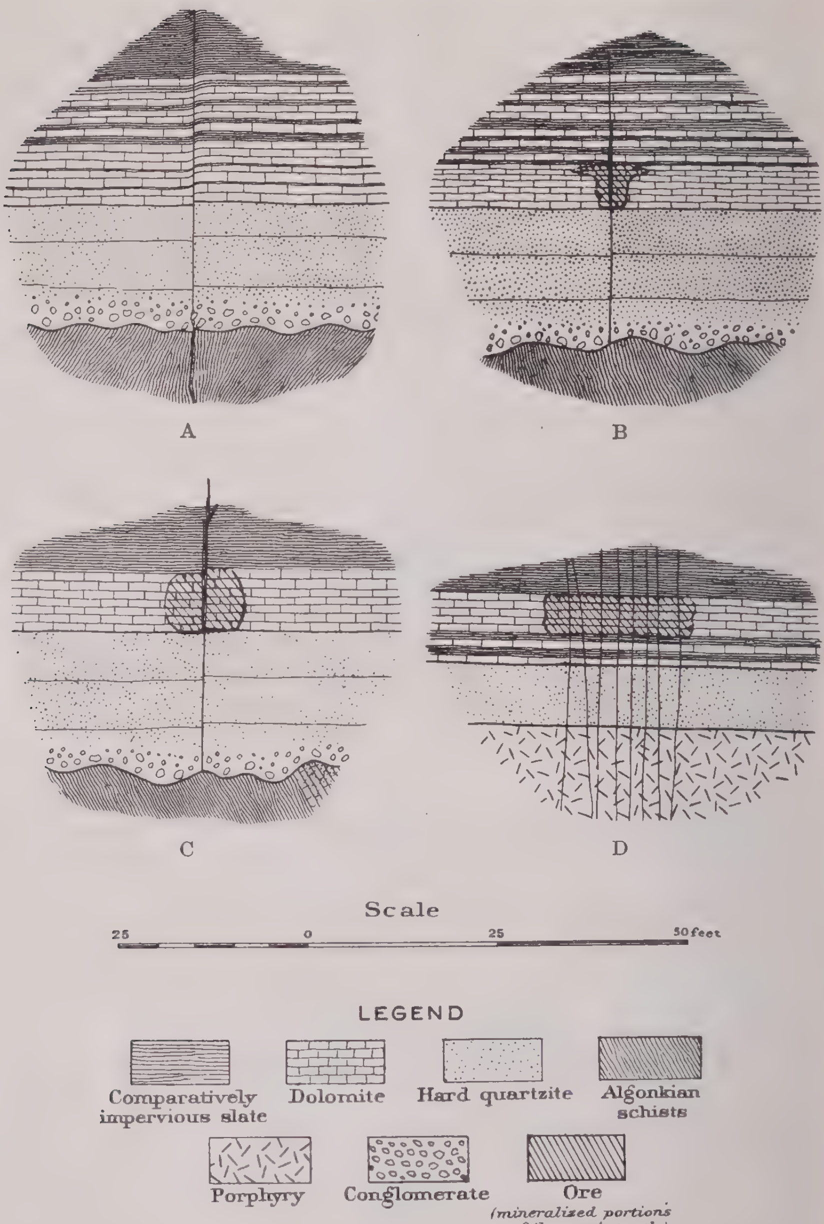
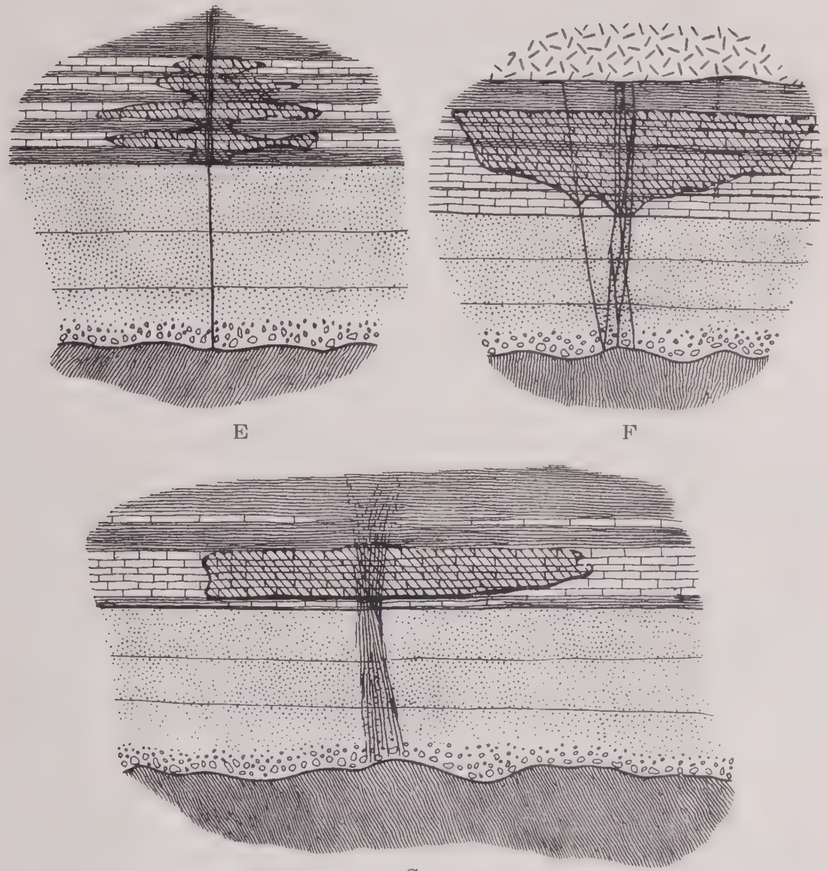


FIG. 14.

Cross-section of silicious orebodies in the Black Hills. A. Unmineralized fissure. B, C. Forms due to single fissures. D. Form due to parallel fissure. (After Irving, Prof. Paper 26, U. S. Geol. Survey.)

cussed and oft-cited Mansfeld copper shales do not in reality belong in this group of flat conformable replacement deposits, which owe their form chiefly to the position and chemical character of the replaced layer.



E F G

FIG. 15.

Cross-section of silicious ore-shoots in the Black Hills. E. Tooth-shaped form produced when fissure intersects alternating soluble and insoluble layers. F. Pear-shaped form due to retarded upflow of mineralizers. G. Free face only where edge of ore crosses limestone. (For legend see Fig. 14.)

Sometimes a replaceable bed or mass of limestone is entirely enclosed in a relatively impervious porphyry mass and the entire rock mass has been replaced. This was the case in some of the Fryer hill orebodies in Leadville. (See Fig. 18 and 19.) As

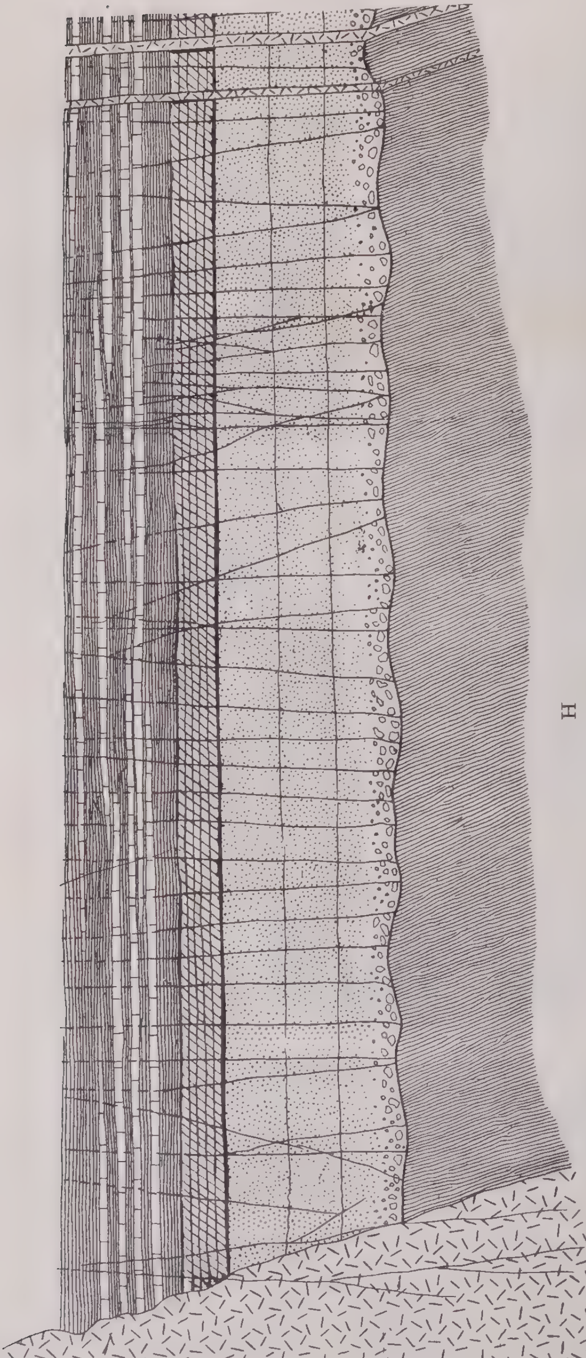


FIG. 16.

Cross-section of a siliclous ore-shoot in the Black Hills. (For legend see Fig. 14.) Ore is conformable to impervious layer both above and below. No free face is shown. (After Irving, U. S. Geol. Surv. Prof. Paper 26.)

these were among the first orebodies studied by S. F. Emmons in Leadville, he was naturally confronted by what seemed to be an extremely difficult problem and it was only when he had seen the orebodies in the incompletely replaced rock their origin of the deposits by replacement of limestone became clear.[13]

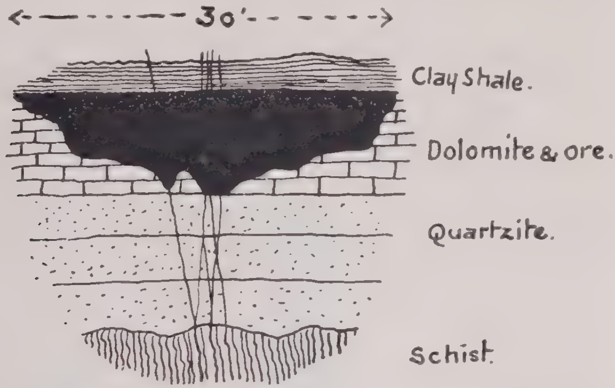


FIG. 17.

Form of shoot influenced by rock structure. Spread of ascending solutions on under side of impervious shales has made shoot wide at top and made a characteristic pear-shaped form. Upper surface of ore is determined by adjacent impervious shales. The lower side is the 'free face.' (Union Mine, Black Hills).

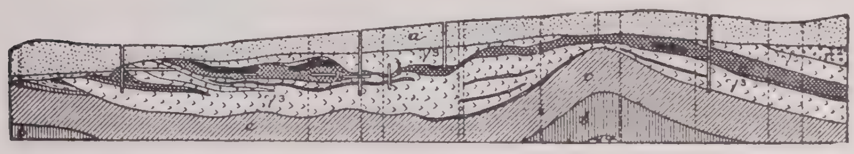


FIG. 18.

Section of Fryer Hill, Leadville, Colorado, showing how entire masses of limestone between two porphyry masses have been replaced and no limestone left. Form of orebody determined entirely by bounding rocks. There is no 'free face.' (After S. F. Emmons, Mon. XII, U. S. Geol. Surv. This is a section reproduced by L. De Launay.)

When more than one susceptible layer is present, that is, when susceptible strata alternate with resistant strata, the resultant orebody will finger out into the surrounding sediments or even enclose unsusceptible layers throughout the entire mass. Such orebodies have, in cross-section, 'saw-tooth' forms or a sort of gridiron structure. An excellent illustration is given in Fig. 20 and also in Fig. 15, E. Masses of susceptible rock such as limestone may

[13]Oral communication.

also be enclosed in irregular porphyry intrusions and may then have any form, so that the replacement will be confined to the susceptible rock, as the Fryer hill orebodies just described, and the resulting ore masses will have the same form as the replaced mass of rock.

EFFECT OF IMPERVIOUS BARRIERS AND CONSTRICTION OF CAVITIES ON FORM.

Waters which circulate rapidly through natural conduits produce less replacement than those which move more slowly or come to rest, probably because more time is afforded for reaction with

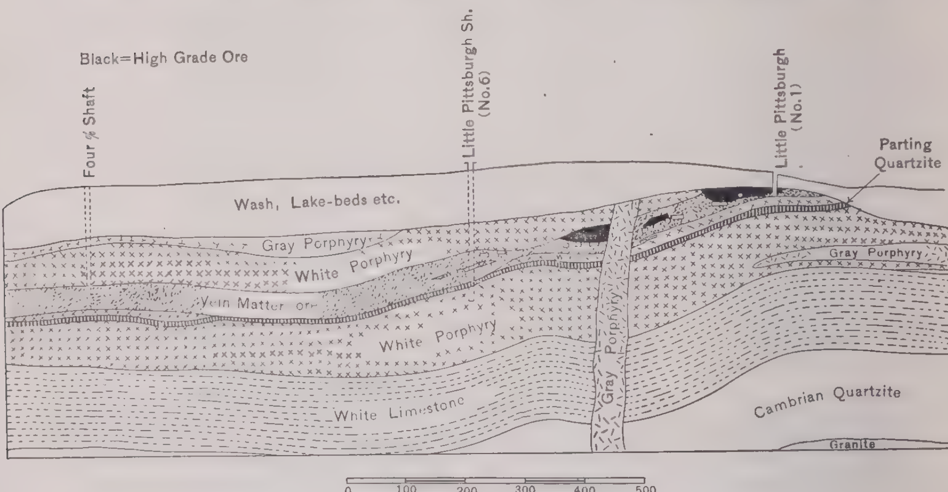


FIG. 19.

Cross-section, of Fryer Hill orebodies at Leadville, Colorado. Shows complete replacement of limestone layer.

the surrounding rock than when circulation is retarded. It thus happens that if impervious barriers lie along the paths of fissures or rocks in which the fissures become lost or constricted, the solutions will be dammed, will spread out beneath or upon the impervious rocks, and the mass of rock replaced at the point of stagnation will be much greater than elsewhere. When waters are ascending (which is generally the case with primary ore masses) this stagnation is greatest beneath an impervious rock, shale, eruptive rock, or other bed, or beneath a rock which has fractured less readily and in which the fissures are comparatively constricted. The result is a large tabular mass roughly horizontal and with its greatest extent immediately below the barrier rock, and perfectly conformable to it, but with a lower surface or 'free face' which is extremely jagged and with long tongue-like apophyses running down into the soluble rock along the supplying fissures and fractures, and finally dying out along them. Along a single fissure such deposits will often have a pear-shaped form in cross-section, such as that shown in Fig. 17 and 21. The impervious barrier in Fig. 21 is a heavy black shale and the replaced rock a quartzite. The fissures, which

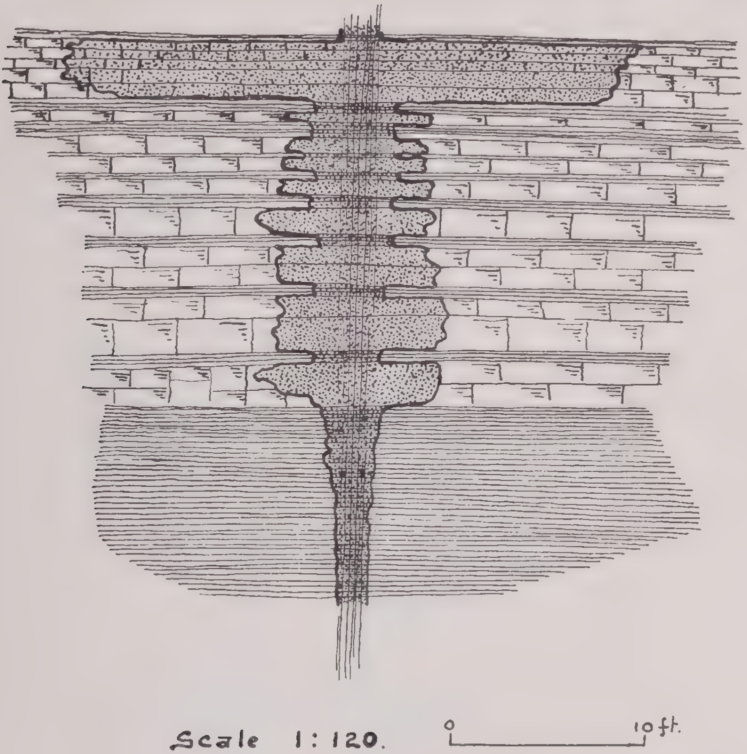


FIG. 20.

Cross-section of ore-shoot in alternating layers of shale and dolomite, Portland, South Dakota. The shales are only slightly replaced by silica, but the ore in the limestone layers runs out to greater distances from the fissure.

are exceedingly minute, are shown in plan in Fig. 22. In this instance there are, in addition to the replacement masses in the quartzite, numbers of filled solution cavities, and the ore masses themselves are usually surrounded by solution cavities which show all of the concave surfaces and other criteria so characteristic of openings formed by solution. The main ore masses, however, seem to have been formed by replacement.

Impervious barriers are effective in stagnating solutions not only when above or below the path of a fissure, but also when they intersect it in a horizontal direction and even if parallel to the zone of fracturing. Thus in the Mineral Farm mine, a portion of which is shown in Fig. 23, a sheet of phonolite is intersected by a set of fractures which pass into it from the surrounding shaly limestone.

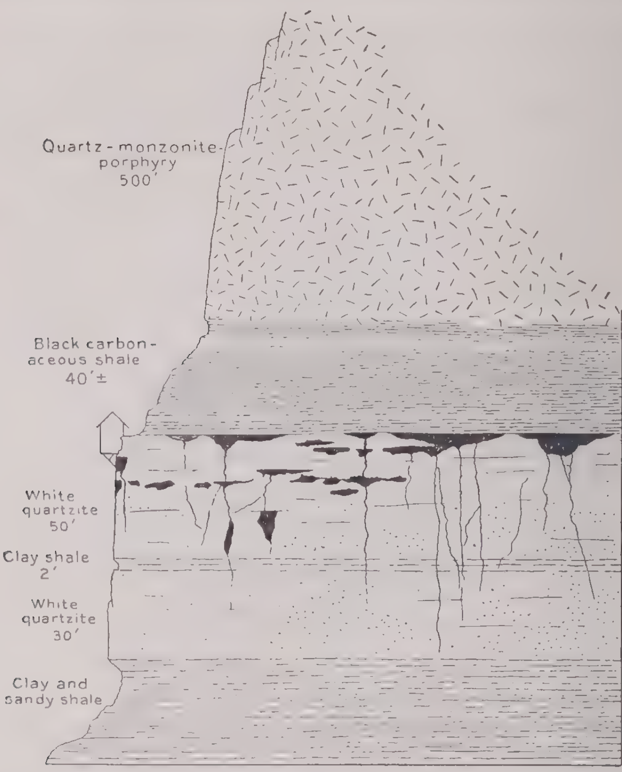


FIG. 21.

Cross-section of the American Nettie mine, showing how pear-shaped shoots of ore have formed beneath impervious barriers of shale. (After J. D. Irving, U. S. Geol. Surv. Bull. 260.)

The ore has completely replaced the rock adjacent to the phonolite, but has not connected the fissure at a distance of 50 ft. from it. In the phonolite itself only a slight alteration a fraction of an inch from the wall has been produced. In the case of the Tornado Mogul shoot, the largest body of refractory silicious ore in the

Black Hills region, the orebody is bounded on one side by a dike of phonolite which has served to assist in the general stagnation of the solutions and has resulted in the production of a very large body of ore (Fig. 16). The same stagnation has been produced in

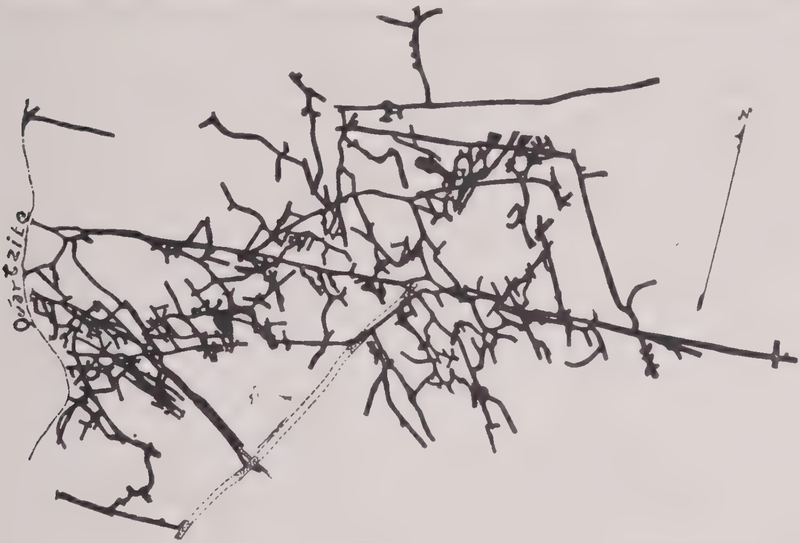


FIG. 22.

Plan of the workings of the American Nettie mine, near Ouray, Colorado. The drifts follow the lines of fissure as shown in the section of Fig. 21. The mine workings thus bring out clearly the fissure systems.

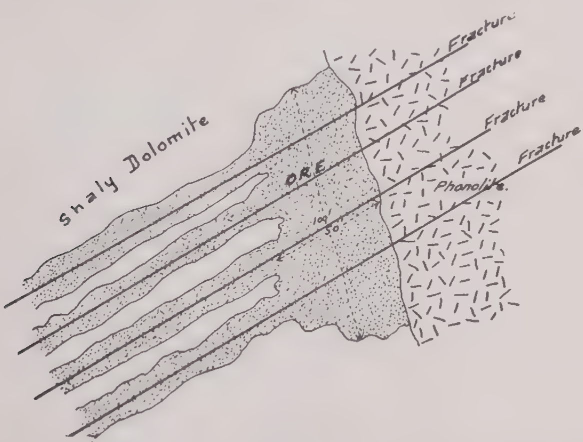


FIG. 23.

Sketch plan of the mineral farm orebody near Portland, South Dakota, showing how replacement of the country rock by silica has proceeded outward from the fractures, but has only completely replaced the intervening rock when the porphyry barrier has dammed up the mineralizing waters.

the Elkhorn mine in Montana, as described by W. H. Weed, where solutions have risen and produced bodies of ore under anticlinal domes of impervious rock.[14] It is to be remembered that in all cases where fissures or openings transect different types of rock the ore will (unless the mass of replaceable rock is very small) have some 'free face' from which the nature of the process may be inferred, and which will show the usual sharp wavy contour or gradual transition to rock that is characteristic of replacement ore deposits.

Stagnation of solutions and consequent increase in the lateral extent of an orebody need not, of course, be determined by an impervious barrier. The constriction of openings which decreases the rapidity of flow, can occur within a single homogeneous rock mass and will cause the solutions to spread laterally and produce the wandering forms which are shown in many of the Leadville orebodies. This will also account for the occurrence of not a few bodies of ore wholly enclosed in limestone in the Leadville district. Most of the ores occur directly beneath the impervious capping, but some of them occur wholly within the limestone, and in these cases it is presumable that the solutions never reached the impervious barrier.

Effect of Manner of Operation of Solutions on Rock.

If the replacement starts from a fissure in a homogeneous rock mass it may be conceived to operate in one of two ways.

1. The solutions may have first penetrated the rock along minute pores until they have saturated it for some distance from the fissure, the limit being set by the balance between the friction of diffusion and the difficulty of escape elsewhere, and the solution may then operate from an innumerable number of separate centres (those farther away being fewer in number). As these separate small masses grow, they gradually interfere until coalescence unites them into one continuous body. At the edges of the body the centres of growth are more widely separated and the resulting masses are disjoined, so that one may pass outward through first a solid mass of ore, then through thickly disseminated particles of ore, then sparsely disseminated particles, and finally into country rock entirely beyond the zone of alteration. It is obvious that this process of replacement may be arrested at any stage, either through lack of further supply of solution or through the final neutraliza-

[14] Weed, W. H., U. S. Geol. Surv., 22nd Ann. Rep., Pt. II, p. 492.

tion of all the chemically active agents in the circulating waters. If the process is arrested early, the replacement will be incomplete, and the deposit will have the form of a mineralized zone throughout which little particles (often perfectly formed crystals) are abundantly scattered but nowhere united into an integral mass. Such replacement is that described by Lindgren from specimens of silicified limestone from Aspen.[15] Replacement here started at a number of centres. Later the perfect crystals so formed have been surrounded by more replacement quartz until the whole mass became replaced. The hexagonal outlines of the earlier formed crystals are still to be seen in the ore, and have been, so to speak, the advance agents of the process. Pyrite cubes embedded in later pyrite are common in Leadville ores and illustrate the same feature.

2. The second manner of operation is quite different and is typically illustrated by the Black Hills silicious gold ores. Here, again taking a single fissure or channel of access as the easiest method of illustration, the boundaries of the ore are abrupt, and all rock from the fissure to the final limit of mineralization is completely replaced. In all of the great multitude of orebodies which I have studied in this region, in no single case was a gradual transition from ore to rock observed. The boundary is often so sharp that no scale is so small that one division of it will not rest on ore and one on country rock. Even in the smallest masses the abrupt transition is observable. In cases of this kind the rock adjacent to the fissure must first have been replaced, then that farther away, and so on until, when the process was arrested, the boundary was left sharp, however far the alteration may have proceeded. In other words, the replacement has advanced like a wave over the country rock until its termination has arrested it at some plane. If the process has operated in this way, the advancing solutions must have found their way constantly through the newly formed ore, and as this is generally quite porous, because of the innumerable little cavities left by the decrease in volume, it has probably gained access to the outer wall in this way. This seems to be further proved as these volume vugs often contain crustified linings of minerals which have been deposited from the ore solutions, such as quartz and fluorite. Where replacement proceeds in this way no disseminated ore is produced.

Whichever of the two ways noted may have been the manner of operation, the process has involved two distinct results, the intro-

[15]Trans. Amer. Inst. Min. Eng., Vol. XXX, p. 628.

duction of the new mineral and the removal of the old. The latter might be termed the disposal of refuse. The dissolved rock has needed to find its way out just as the old has needed to find its way in. It is not difficult to see how this could have occurred, because it is evident that the high temperature and dilution of ore-bearing solutions must have been accompanied by a division into ions which may have traveled back and forth through the solutions during the process, the ions of dissolved material working back along the same paths as those of new material which were proceeding in the opposite direction. In some cases, when the solutions have been apparently saturated with dissolved rock at the close of the process, the original rock substance has been again precipitated in the volume cavities, filling in the spaces of the vugs between the minute crustified linings which occur in them. Such minerals might well be termed 'renascent minerals', to distinguish them from the 'juvenile' minerals deposited from the original solutions. It is aside from the purpose of this paper to enter further into the questions of physical chemistry involved in the process, for the problems are difficult and complex and only to be inferred from geological evidence; but these suggestions may serve to stimulate experimental work.

Effect of the Amount of Material Supplied in Solution.

If the supply of mineralizing water is great and its introduction extends over a long period of time, the replacement will extend much farther from the channel of access than if it is very slight. This is well illustrated in the comparative series of cross-sections of ore-shoots in the Black Hills (Fig. 14, 15, and 16). Ore-shoots frequently terminate along their strike, although the fracture or opening may continue, and is sometimes as large as that where the orebody is extensive. The supply of solution seems to have been confined chiefly to certain areas and its amount has been insufficient to produce extensive replacement except in the heart of the channels of flow. Cross-sections A, B, and C (Fig. 14) show progressively increasing amounts of mineralization from single verticals. When all of the causes which influence the form of a replacement orebody are together present in a single orebody, namely, form and distribution of channels of access, varying porosity, varying susceptibility, and varying supply of mine waters—it is often difficult to determine what cause has exerted the maximum effect; but it rarely happens that some portion of an orebody cannot be found where one alone has been the determining factor.

Rocks Affected by Replacement.

Although this paper is not intended to be a discussion of the chemical side of replacement processes, a few words as to the susceptibility of the main rock groups are necessary.

It has been clearly shown by previous writers, notably Lindgren, that replacement may occur not only in calcite, dolomite, and other readily soluble minerals, but in a great variety of other more insoluble minerals, a few only escaping. Even quartz suffers oftentimes at the hands of calcite, siderite, and minerals ordinarily considered quite soluble. It therefore follows that rocks made up of aggregates of these minerals will suffer replacement. As different minerals are differently affected by solutions, rocks will be more or less completely replaced according as they are made up of aggregates of the same or of different minerals.

Pure or fairly pure limestones, being composed of aggregates of calcite or dolomite grains with comparatively little other material and that scattered widely through the rock, are far more extensively and completely replaced than rocks of any other type. The disseminated types of replacement bodies are therefore relatively rare in them. As alumina and silica increase, they are the receptacles for less and less pure ore masses, the alumina and silica often persisting unaltered in the ore resulting from replacement. Shale bands and rounded detrital quartz grains, therefore remain unaffected and often constitute valuable criteria for the recognition of the process. Sandstones and quartzites are far less *extensively* affected, though they are perhaps as *often* replaced as is limestone. Deposits in them, owing to their greater porosity, are apt to be disseminated and incomplete, starting as they do from innumerable centres at the same time and proceeding only slowly and with difficulty in so resistant a mineral. In the calcareous sandstones where the cement is calcite, the calcite is often replaced and the detrital grains of quartz left unaltered. In such replacements it is frequently a matter of extreme difficulty to distinguish between impregnations, or the filling of intergranular spaces, and the actual replacement of the component grains of the original rock.

The least easily attacked rocks among the sediments are those containing high percentages of alumina. Such are the clay shales and their metamorphic derivatives. Those containing these high percentages of alumina suffer least and will often persist without alteration when interbedded with limestone that is wholly replaced. Shales with high percentages of lime are often extensively replaced.

With the igneous rocks, which are essentially heterogeneous, the conditions are usually different. They are aggregates of different minerals which are very differently affected by any given solution. For this reason igneous rocks are rarely wholly replaced, and deposits formed in them generally disseminated or scattered; that is, solutions here exercised a selective effect, replacing some minerals and leaving others untouched or affecting them in a different way. Furthermore, the pore space for the access of solutions is extremely small, as will be shown later. Instances of this type of replacement are Ely, Nevada, the porphyry coppers of Bingham, Utah, and other similar occurrences.

The Criteria of Replacement.

General.

Determination of the genesis of an orebody resulting from replacement may be made through application of many different criteria. It rarely happens that all of these may be applied to a single deposit, but in most cases one or more of them will be available. Many of them may be applied directly in the field, others require the use of the microscope. That the discussion which follows may be more easily understood, the appended classification of criteria is given: (1) Presence of complete crystals in foreign rock masses; (2) preservation of rock structures; (3) intersection of rock structures; (4) absence of concave structures; (5) absence of crustification; (6) presence of unsupported nuclei; (7) relation to fissures and other cavities; (8) form; (9) decrease in volume due to changes in composition; (10) excess of volume of introduced mineral over original pore space of rock.

It is important to understand that the criteria which are most serviceable in recognizing replacement may most of them be eliminated by regional metamorphism. Any class of ore deposit may suffer metamorphism, together with the enclosing rocks. Original structures are then completely obliterated. If such metamorphism is extreme, ore deposits afford no criteria as to the part played by replacement in their original formation.

Complete Crystals in Country Rock.

At the edges of those replacement masses in which the transition from ore to rock is gradual, or in cases where the new mineral is sparsely disseminated through the country rock in the vicinity of some minute crevice or cavity, an examination by the microscope will often show that the new mineral has complete crystalline form, that is, has all of its faces developed. Crystals which grow in cavities are attached to the walls of the openings in which they are deposited or to other earlier deposited crystals and therefore never have all of their faces completely developed. Even where not perfectly developed, the relation of some one crystal face to the grains of the original rock, affords an excellent criterion. Crystals of this kind may occur in sedimentary, igneous, or metamorphic rocks, and their value as indications of replacement is in each case determined by different criteria.

COMPLETE CRYSTALS IN SEDIMENTARY ROCK.

Sandstones and quartzites consist of more or less water-worn grains of quartz deposited in the form of solid particles. In quartzites the grains are cemented by silica added later, but can usually be distinguished from it. Complete crystals of pyrite, fluorite, galena, siderite, tourmaline, and other minerals, often occur in such rocks showing perfectly or partly bounded crystals embedded partly in one grain and partly in another, as the crystal faces extend through and intersect two or more grains of the original quartz. W. Lindgren has described from the Helena & Frisco mine in the Coeur d'Alene district a quartzite partly replaced by siderite and pyrite.[16] He has also cited[17] a case described from Mount Bischoff, Tasmania, by W. von Fircks in which needles of tourmaline transect the clastic grains of quartz which they replace, or are entirely within them. Many other illustrations might be given.

It is evident that these crystals could not have been deposited with the sand grains of the original rock, first because they are often too soft or friable to stand attrition without being destroyed, or at least marred during deposition, and second, because the solid particles of quartz could not afterward have been moulded around them. Nor could they have started their growth in the interstices between the quartz grains and forced the grains apart by virtue of the force of crystalline growth, for that would not have resulted in the carving out of the perfectly fitting cavities in which they are found. Microscopic examination of many such specimens also shows that in no case except that of rocks already metamorphosed do the constituent grains of the original rock show any strain phenomena such as wavy extinction or any other optical evidence of strain. The only other possible explanation of their presence aside

[16]Trans. Amer. Inst. Min. Eng., Vol. XXX, p. 635.
[17]*Ibid*, p. 637.

from replacement is that cavities have first been dissolved by circulating waters of exactly the shape and size of the crystals to be later deposited, a view which ascribes to circulating waters a sentient power which is manifestly absurd. If they be formed by replacement, however, no such difficulties arise. Solutions containing the ingredients of the new minerals dissolve the old and substitute the new in its place, molecule by molecule, so that no discrepancy between space and crystal grain can occur that is larger than the diameter of a single molecule. It is possible that the force exerted by the crystalline growth of the new mineral has increased the pressure around its periphery to such an extent as to materially aid in the solution of the old mineral and the simultaneous substitution of the new.

Aside from their relation to individual grains, crystals of this kind may also intersect the sedimentary bands of the original rock or other minute and easily recognizable original structures, such as fossils, cross-bedding layers, etc., showing that they have been introduced subsequent to the formation of these structures. In limestone such well developed crystals or groups of crystals are even more frequent. Fig. 24 shows large crystals of barite developed in

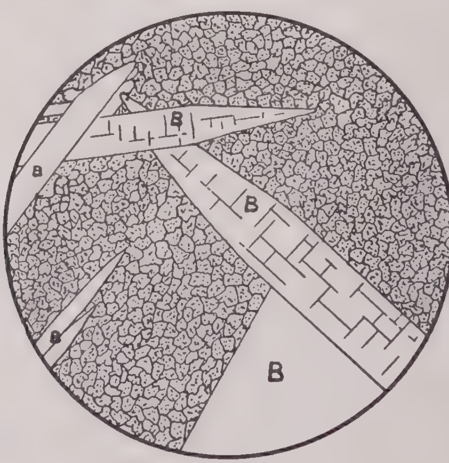


Fig. 24.

Barite replacing limestone. B, barite in fine-grained limestone.

a fine-grained granular limestone. Fig. 25 (after Lindgren) shows crystals and clusters of crystals developed by replacement in limestone. In shales the case is somewhat different. Here the component particles of the original rock are extremely fine and likewise the banding. Newly introduced crystals can grow in such rocks by forcing aside the shaly material and compressing it to one side or the other. Fig. 26 illustrates an instance noted by T. C. Chamberlin in which the crystals of blende may be seen with the banding

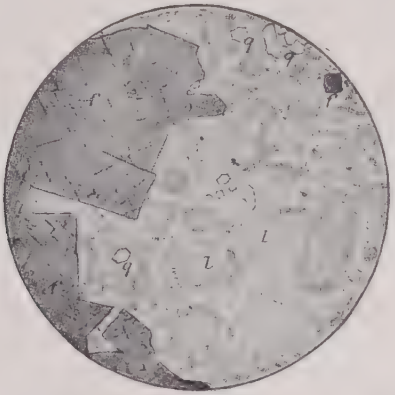


FIG. 25.

Fluorite replacing limestone, Florence mine, Judith mountains, Montana. f, fluorite; l, limestone; q, secondary quartz. Note how crystal boundaries are perfectly developed on fluorite and quartz crystals. (After W. Lindgren.)

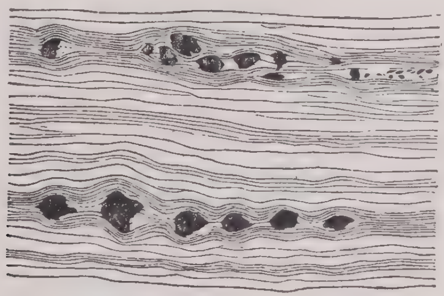


FIG. 26.

Section of a portion of 'speckle jack,' showing the manner in which crystals of blende are embedded in the rock and the curvature of the laminae about them. (After T. C. Chamberlin, 'Geology of Wisconsin,' Vol. IV, p. 474).

of the shales passing up around them. Fig. 27, however, shows a specimen of ore in which the galena fairly transects the original shale bands of the rock and is evidently a replacement. This is taken from a drawing made by myself from a specimen from the Federal Lead Company's mine in Missouri. It is important in

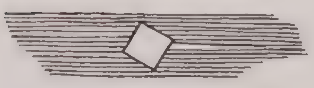


FIG. 27.

Cube of galena replacing shaly limestone. The crystal squarely intersects the shaly layers. Drawn from specimen from mines of Federal Lead Co., Flat River, Missouri.

dealing with shales to determine if the crystals have grown by a distortion of the original layers of rock material or by actual replacement.

METAMORPHIC ROCKS.

In metamorphic rocks the same feature may often be observed. In certain specimens of ore from the Homestake mine crystals of arsenopyrite have developed in the schist, and the schistose structures pass up around them just as in the case of shales, forming peculiar knots in the rock when it is split without actually disclosing the kernel of ore beneath. In general, in metamorphic rocks the same criteria may be observed, but in addition it is important to determine if the newly introduced crystals, first, intersect the metamorphic minerals such as garnet, staurolite, etc.; second, if they intersect and are hence later than metamorphic structures such as schistosity; and third, if they themselves are entirely free from shattering or strain due to metamorphism. If these three factors are determined, it is safe to say that they have been introduced after metamorphism and their intersection of typical metamorphic minerals may then be taken as positive evidence of replacement.

In regard to the evidence of crystals such as those just described, it will be interesting to quote Lindgren's statement:[18]

"The only decisive criterion [of molecular replacement] is that of metasomatic pseudomorphism involving the proof (generally furnished by microscopic study) as to whether simultaneous dissolution and deposition have actually taken place. The most satisfactory proof is the distinct alteration of well defined crystals (or at least well defined grains) of the original mineral into the secondary mineral in such a way that the latter projects into the former in prisms and fibres, having crystalline outlines. Another proof is afforded by sharply defined crystals of the secondary embedded in the primary mineral without any break between their surfaces; but in this case it must be clear that the replacing mineral is really secondary, and was not formed before the primary. Another

[18]Trans. Amer. Inst. Min. Eng. Vol. XXX, p. 595-596.

satisfactory proof is given, if, for instance, in a sandstone the newly formed mineral has in part a crystalline form and its surfaces squarely intersect the grains of clastic material which it partly replaces."

IGNEOUS ROCKS.

Complete or partly developed crystals in igneous rocks can be attributed with certainty to replacement only when there is no doubt as to their secondary nature. The constituent minerals of such rocks have crystallized from molten magmas, and those that have crystallized first will often show well developed crystalline forms, the other minerals moulding themselves about the faces of the earlier formed crystals. Quartz, for instance, frequently occurs in doubly terminated prisms in rhyolite porphyries in such a manner that all of its faces are perfectly developed, but as it is one of the ordinary original constituents of the rock, no confusion can arise as to its primary origin.

With these rocks only such minerals as cannot occur under igneous conditions can, from the crystalline form of the mineral alone, or from its relation to the adjoining grains of the rock, be ascribed to replacement. When such minerals as siderite, calcite, arsenopyrite, and other minerals not characteristic of igneous rocks occur in them with faces which intersect or interpenetrate the other minerals of the rock, little doubt exists as to their secondary nature. With the other more usual minerals of ore deposits such as galena, pyrite, sphalerite, chalcopyrite, or pyrrhotite, the case is more difficult; for, while the occurrence of such minerals as original crystallizations from magmas is rare, many petrographers believe that the metallic sulphides form in igneous rocks as primary minerals, and their intergrowth into adjoining mineral grains cannot therefore be used with certainty. Assistance is furnished by the relation of mineral grains of the supposed new mineral to channels of access into the rocks. If pyrite, for instance, is thickly disseminated in crystals or partly faceted grains through the rock in the neighborhood of a crack or other opening and then gradually dies out as distance from the conduit is gained until in the normal rock it is absent, its crystalline form and the transection of the other constituent grains by one of its crystal faces may with certainty be used as an indication of its formation by replacement. Its relation to the fissure is enough to establish the fact that it is not an original igneous mineral. Its relation to the other grains will then determine whether it is a cavity filling or a replacement. Assistance is also furnished by the character of the mineral grains which it intersects. Thus a pyrite crystal which cuts into one of the faces of a perfectly developed quartz phenocryst is probably formed by replacement, since the phenocryst would have been an early crystallization in the magma and would probably not have included a pyrite crystal partly in the mass, but would have thrust it aside into the still molten mass or else have included it entirely, so that it could not be forced out during crystallization. The association of metallic minerals with other products of thermal alteration such as sericite, while absent in all fresh and unaltered rock, will also serve to render this criterion of value.

Preservation of Structures.

GENERAL.

All rocks are characterized by certain structural or textural features which are either peculiar to them or have been later induced in them by the action of pressure or dislocation. Original structures such as stratification, cross-bedding, fossils, or fossil groups, are characteristic of sedimentary rocks; phenocrysts of igneous rocks; and schistose and gneissoid structures of metamorphic rocks. Such structures are rarely to be confused with any of the structures met with in epigenetic ore masses. Later disturbance may induce secondary structures in rock masses such as folds, brecciated structures, joints, minute faults, etc., and these may extend through considerable areas of a rock mass. Original rock structures are often preserved in ore masses and these serve as an excellent indication of replacement. There is probably no criterion of replacement which may be quite so readily detected nor any which is so generally serviceable.

In order that a structure may serve as a definite criterion for replacement it must either be such as is definitely characteristic of the original rock or a later induced structure that can be shown to have existed prior to ore deposition. If a structure can be independently formed in an ore mass which fills a cavity, it will be of less certain value as a criterion. There is usually no difficulty in making the distinction for original rock structures, as these are generally characteristic and are not often easily confused with ore structures. With later induced structures such as folds, faults, or joints, the matter is not so simple, since the ore itself may suffer like deformation. In such cases the intersection of the secondary structures by the ore mass in such a way that the structure is partly in ore and partly in the rock will often be of assistance. This criterion will be discussed in the following pages.

The original structural features of rock masses which may be retained in ore are of all sizes, from those which are large enough to be readily seen in the field to those which are so minute that the microscope is needed for their identification. It is, in general, true that the preservation of larger rock structures in the ore is more readily serviceable for the detection of replacement and that the more minute structures approach more nearly a positive proof of the molecular nature of the process. No preservation of rock structure, however minute, can serve to distinguish absolutely between molecular replacement and creation by solution of very small spaces with later mechanical deposition in them. The microscope does not afford a means of detecting structures which approach the actual sizes of molecules. This criterion can therefore only be used as a strong indication of the process and the student must rely on the complete crystals mentioned on pages 253-258 for a proof of its ultimate molecular nature. From the evidence afforded by such crystals, where they occur as outliers of ore masses which show other criteria, the molecular nature of the process may be inferred for the entire mass, and the preservation of structures in the ore mass as a whole may often be carried down to such small microscopic features that, while not amounting to absolute proof, little doubt is left that the interchange of material is of a molecular character.

The rock structures that may be preserved in ore masses may be conveniently grouped as follows:

Original Rock Structures	Preserved in ore masses replacing sedimentary rocks.	1. Stratification. 2. Cross-bedding. 3. Fossils. 4. Dolomitization Rhombs.
	Preserved in ore masses replacing igneous rocks.	5. Phenocrysts.
Induced Rock Structures	Preserved in ore masses replacing any rock.	6. Joints and Faults. 7. Brecciated Structures. 8. Folded Structures.

In this table the structures characteristic of metamorphic rocks such as schistosity and gneissoid structure are not mentioned. They are omitted because, like vesicular structures in lava and some other features, they have not yet been detected in any ore mass so far studied in relation to replacement. This is in part due to the resistant nature of the rocks in which such structures occur and the different chemical character of the component minerals. Replacement of such rocks is often incomplete and results in disseminated grains of mineral scattered through the rock which are too far separated to show any preservation of original structure. It is probable, however, that further study will much increase the number of such preserved structures, and well defined schistose or gneissoid structure would then afford a valuable criterion.

CHARACTER OF THE ORE IN WHICH STRUCTURES ARE PRESERVED.

The preservation of structures is more perfectly carried out in some classes of ore than in others. Silica preserves original structures more perfectly than other minerals, and often occurs in such minute grains that only with the microscope is it possible to discover the individual grains of the replacing mineral. An interesting instance is the preservation of the minute structure of the wood in the case of silicified trees. With the sulphides the preservation of structures is not so easy to detect on account of the opaque nature of the mineral and the tendency of the component grains to grow by interpenetration into the grains of the original rock and the consequent obliteration of all of the more minute structural features. In some cases, however, fossil shells preserved in pyrite have been noted, and stratification planes are often so preserved, though usually less perfectly than in ores largely composed of secondary silica. It is not always easy to determine just what causes the retention of the form of the original structure. In the case of limestones replaced by silica it is partly due to the arrangement of the quartz grains in aggregates of different sizes (see Fig. 32) and partly to the inclusion in the replacing quartz grains of the original organic impurities of the limestone. Foraminiferal test in the upper of the two cuts in Fig. 32 shows this; that is, the quartz which has replaced the rock has not disturbed the arrangement of the original particles of foreign material of the rock, but has replaced the calcite about them and left them in their original position. In consequence, an examination of silicious ore without the polarizer will show the original outline of a foraminiferal test or dolomite rhomb as determined by minute unreplaceable particles of foreign matter, but the application of the polarizer shows that the place of the lime has been entirely taken by silica.

ORIGINAL ROCK STRUCTURES.

Stratification.—All unaltered sedimentary rocks are characterized by a division into layers or strata, which may vary in thickness from the thinness of paper to a hundred feet or more. When the beds are of great thickness no preservation of them in the ore mass is usually noticeable, as the orebodies are then often of less size than the individual beds or layers, but when the layers are thin they have been found frequently preserved in ore masses. As orebodies which fill open cavities are often banded, it is important not to confuse preserved stratification with banded structure. In most cases the distinction is not difficult. Preserved stratification is always comformable or continuous with that of the enclosing rock, while banding due to ore deposition is often at variance with it. Silicification, for instance, of shaly limestone occurs in the Cambrian sediments of the Black Hills of South Dakota. The sediments are intersected by minute fissures and large masses of ore have been formed by the replacement of this limestone chiefly by silica and a little pyrite. The banding of the original rock extends continuously into and through the ore and again into the country rock on the other side, although the substance of the rock is entirely altered to ore. In some cases this banding is so perfectly preserved that it is impossible to distinguish between country rock and ore except by a slight difference in color and the hard brittleness of the material. Fig. 11, page 226, shows a sketch of a small offshoot in the Dividend mine near Portland, South Dakota, in which this continuity of banding is admirably illustrated. Fig. 28 is from a photograph of an ore face in the Union mine near Terry, South Dakota, showing the preservation of banding in the ore. The boundary between the ore and the adjoining rock is usually very sharp and the strata pass uninterruptedly across the line of demarcation, being composed on one side entirely of carbonates and on the other entirely of silica and pyrite. As is usual in replacements where the mineral introduced is chiefly silica, the structure is more perfectly preserved than in the case of solid masses of metallic sulphides. The regularity is somewhat disturbed by a slight decrease in volume, as the ore has less volume than the rock replaced, and the ore is thus characterized by a large number of irregular vugs or cavities which are not present in the original rock. The bedding planes are even more regular than indicated by the photograph, as the broken face is irregular and the foreshortening produced by the perspective of the photograph has produced a wavy appearance

Fig. 28.

Face of ore in the No. 2 shoot, Union mine, near Terry, Black Hills, South Dakota. The original rock is thin-bedded shaly limestone, the ore is silica with small amounts of pyrite and fluorite, with gold to the amount of about $20. The stratification is here shown preserved in the orebody, although the limestone has been entirely altered to ore. The scale is shown by the shovel handle. (After Irving, U. S. Geol. Surv. Prof. Paper 26, Plate XVI.)

that does not actually exist in this ore face. An examination also of Fig. 20, and the comparative series of cross-sections shown in Fig. 14, 15, and 16, will give an even better idea of the manner in which the bedded structure passes continuously through the ore.

On the other hand, banding due to crustification or the deposition of ore in layers is usually independent of the rock structure. In some cases it will form a lining to the entire open space as shown in the lead and zinc ores of the Iowa-Wisconsin district. Fig.

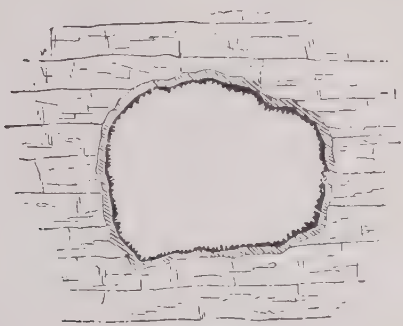


FIG. 29.

Cavity formed by solution and afterward coated with a crustified lining of pyrite next the rock and blende attached. The banding of the sulphides is independent of the rock structure. (After T. C. Chamberlin, 'Geology of Wisconsin,' Vol. IV, p. 467.)

29 shows this feature. G. O. Smith and Warren Tower cite an instance from the Tintic district in Utah where the banding of the ore was unconformable with that of the enclosing limestone: "In the Eureka Hill mine, 300-ft. level, a large cave deposit was found, consisting of alternating bands of quartz and cerussite. These bands are horizontal and at right angles to the stratification of the limestone."[19]

In such cases as these, little difficulty will be experienced in making the distinction between preserved bedding and ore banding, nor have I ever observed any instance in which the distinction offered any difficulty. It is conceivable, however, that in veins formed by the filling of spaces of separation between rock strata where crustification is parallel with the bedding of the enclosing rock, confusion might arise and in such cases some other criterion will need to be sought.

[19]Tower, W., and Smith, G. O. 'Geology and Mineral Industry of the Tintic District, Utah,' U. S. Geol. Surv., 19th Ann. Rep., Pt. III, Pl. LXXXIV.

Again, in using this preserved stratification as a criterion, it is important to distinguish between preserved bedding planes and residual bedding planes. The laminae of sediments may be formed either by a difference in the size of the grains composing them or by a difference in the chemical composition of the material. In the illustration given, the rock is composed entirely of layers of carbonate of lime and magnesia with very small quantities of clayey material. The entire rock has therefore been replaced and the bedding planes in the ore represent preserved structure. In many instances (very common in the Black Hills silicious ore districts) the rock is made up of alternate laminae of clay shale and carbonate of lime and magnesia. The lime in these cases has often been extensively replaced, but the resistant nature of the shale has caused them to remain unaffected in the ore. Such persistent layers are most properly termed 'residual structures.' Their significance as an indication of replacement is discussed under the heading of unsupported structures.

In addition to the Black Hills of South Dakota, the retention of sedimentary banding in ore masses has been observed in a number of places of which Leadville, Colorado, and Bingham, Utah, are interesting examples. The sulphide masses of Leadville are composed of pyrite, sphalerite, and some galena; chalcopyrite is in very small amount in the unenriched primary ores. When these ore masses are enclosed in beds of pure limestone which is uninterrupted by any bands of more resistant and unreplaceable shales, the entire mass of the rock has often been replaced, and it frequently happens that there is in a freshly broken face of ore no evidence of banding. If, however, the face has stood exposed for some months, so that layers of dust have accumulated on it, the dust adheres to the sulphides which have replaced one layer in a slightly different manner from that which has replaced the next adjoining layer. This is probably due to a slightly different arrangement of mineral grains in the ore produced by the varying susceptibility of the direct layers to replacement, and serves to preserve in a faint but suggestive manner the original banding of the sediments. S. F. Emmons,[20] in discussing the origin of these sulphide masses, says:

"In the great bodies of the A. Y., Minnie, and adjoining mines, not only could every detail of the granular structure, joints, and cleavage of the original limestone be detected at times in the sulphide ore, but even the cracks in the top. In abandoned drifts

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[20]Emmons, S. F. Trans. Amer. Inst. Min. Eng., Vol. XXIII, p. 602.

where limestone dust had accumulated on the walls, one would have supposed the walls to be all limestone until the breaking off of a fresh fragment by the hammer showed the metallic gleam beneath."

In Tintic, Utah, Tower and Smith have described the orebodies of some of the mines as showing the structural features of the limestone, but the bedding of the stratified rocks is not represented as being preserved.

The large copper shoots which occur in limestone at Bingham, Utah, and which are shown in plan in Fig. 30, show a remarkable preservation of the stratification of the country rock. As is usual in sulphide ores, this banding is less easily observed and less perfect than in replacement by silica; but its continuity with the bands in the adjoining rock is striking. These orebodies are thus described by J. M. Boutwell:[21]

"As was stated in the description of the structure of the copper shoots, the broad characteristic of this structure is banding. This banding is not like the crustified or even the roughly banded structure of the lodes, but is a bedding which in form is identical with the bedding of the strata. The chief difference is in composition, these beds being composed of ore instead of limestone or quartzite. Bedded structure characterizes alike miniature orebodies, mineralized wall rock adjacent to seams, and large lenticular ore-shoots. Thus mineralization adjacent to fissures in limestone took place along beds. Further, the marked deposition of ore along certain beds, and the slight deposition along others, appear to indicate a selective tendency on the part of mineral in solution for more soluble beds. Similarly, in small shoots the massive structure is a bedding of massive ore which is more extensive in some beds than in others. Finally, the immense lenses of cupriferous pyrite, that is, those in the Highland Boy, exhibit the same massive bedded structure. This selective action leads to a very irregular periphery. The transition from massive, solid ore to barren country on the periphery is not sharp, as in the case of the lodes, where the transition from the rich bands to barren wall rock is well defined. On the contrary, it is gradual, passing from the bed of rich copper sulphide through lean copper ore, still poorer ore, merely stained country, to normal, barren marble country. Although the composition changes from ore to barren country rock, the structure is persistent, so that a bed of ore is

[21]Boutwell, J. M. U. S. Geol. Surv. Prof. Paper No. 38, p. 193.

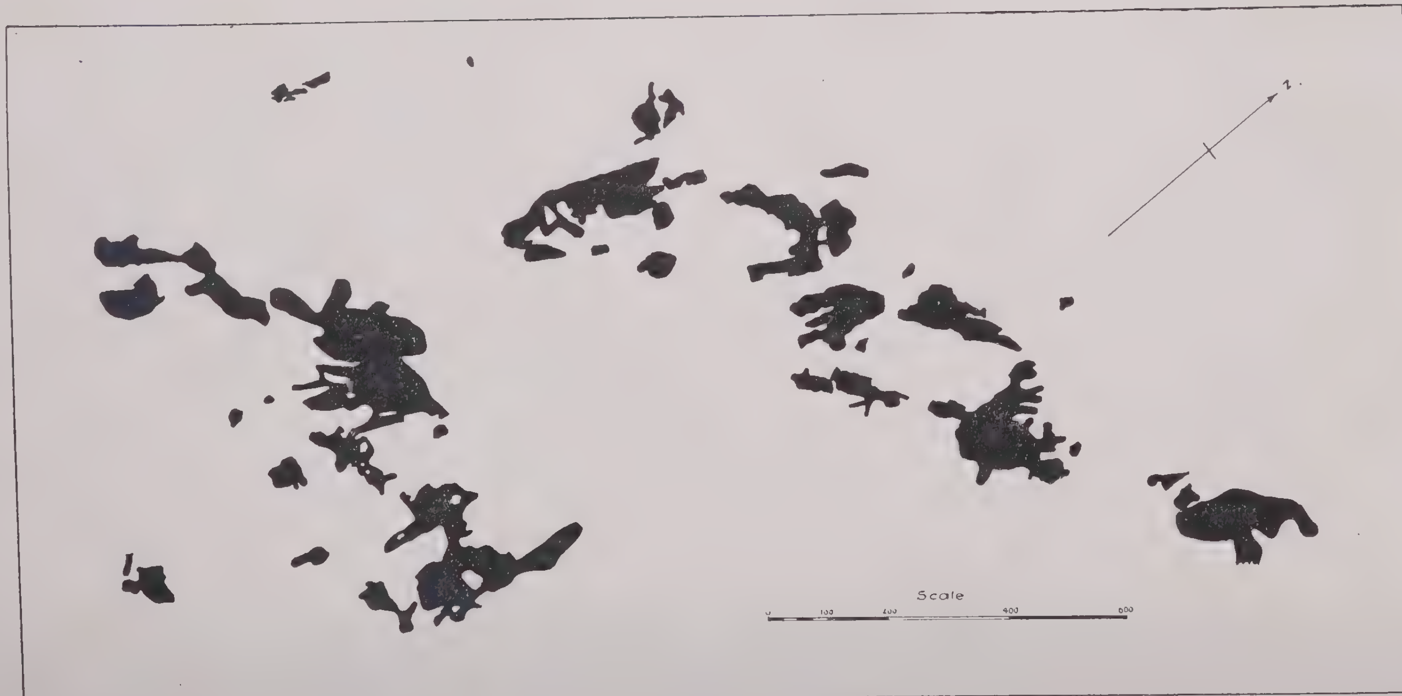


FIG. 30.

Plan of ore-shoots in Jordan and 'Highland' limestones, Old Jordan mine, Bingham, Utah. These orebodies show the preservation of the stratification of the enclosing rock in the ore. Adapted from J. M. Boutwell, U. S. Geol. Surv. Prof. Paper 38, Pl. XL. As shown in the original report the orebodies are shown by dotted lines. These have been colored black in this cut and the mine workings omitted.)

clearly seen to be a portion of the same bed of country rock; in other words, the ore has retained the bedded structure of its country rock. * * * The foregoing general examination of the copper ore in limestone indicates that the copper shoots in limestone have a bedded structure, and that the bedding corresponds to the stratification of the country. These features are generally considered to signify in a broad way that the ore has taken place of the country rock by substitution. They are characteristic of 'replacement' deposits and accordingly suggest that the copper deposits in limestone were formed by replacement."

Cross-bedding.—So far as I have observed or been able to discover in the literature, no cross-bedded structures are known to have been preserved in the ore of replacement orebodies; but there is little doubt that such structures will be found if a careful search is made for them in ore masses which occur in rocks which themselves have such structures.

Fossils.—The true nature of molecular replacement was first recognized in the study of fossils in which the substance of the original shell was altered but the form of the fossils preserved. In the early history of the study the process of replacement of fossils was termed petrefaction and quite a little is to be found in the literature in regard to it. In his text-book of geology, Archibald Geikie describes the process in the following words:[22]

"The original substance is molecularly replaced by mineral matter with partial or entire preservation of original structure. This is the only true petrefaction. The process consists in the abstraction of the organic substances, molecule by molecule, and their replacement by precipitated mineral matter. So gradual and thorough has this interchange often been, that the minutest structure of plant and animal have been perfectly preserved. Silicified wood is a familiar example."

He then quotes the following passage from J. Roth:[23]

"The chief substance which has replaced organic forms in rock formations is calcite, either crystalline or in an amorphous granular condition. In assuming a crystalline (or fibrous) form this mineral has often observed a symmetrical grouping of its component individuals, these being usually placed with their long axes perpendicular to the surface of an organism. In many cases among invertebrate remains the calcite now visible is pseudomorphous after

[22]Text-Book of Geology, 1st Ed., p. 610.
[23]Roth, J. 'Chemical Geology,' Vol. I, p. 605.

aragonite. Next in abundance as a petrifying medium is silica, most commonly in the colloid form (calcedony, opal), but also as quartz. It is specially frequent in some limestones, as chert and flint, replacing the carbonate of lime in molluscs, echinoderms, corals, etc. It also occurs in irregular aggregates in which organisms are sometimes beautifully preserved. It forms a frequent material for the petrifaction of fossil wood. Silicification, or the replacement of organisms by silica, is the process by which minute organic structures have been most perfectly preserved. In a microscopic section of silicified wood, the organization of the original plant may be as distinct as in the section of any modern tree. Pyrite and marcasite are common replacing minerals, especially in argillaceous deposits, as, for example, among the clays of Jurassic and Cretaceous formations. Siderite has played a similar part among the ironstones of the coal-measures, where shells (*Anthracosia*, etc.,) and plants have been replaced by it. Many other minerals are occasionally found to have been substituted for the original substance of organic remains. Among these may be mentioned glauconite (replacing or filling foraminifera), vivianite (specially frequent as a coating on the weathered surface of scales and bones), barytes, celestine, gypsum, talc, lead sulphate, carbonate, and sulphide, copper sulphide and native copper, haematite and limonite, zinc carbonate and sulphide, cinnabar, sulphur, fluorite, phosphorite.''

This and similar passages will show how clearly the early geologists appreciated the distinction between preservation of internal structures and the filling of moulds left by the solution of a shell and the later filling of the opening.

In using fossils altered into ore as a criterion, distinction between solution and deposition, and replacement is particularly important. In the case of larger structures, the distinction is not difficult. For more minute textural features, by one familiar with the internal structure of calcareous organisms, the characteristic structure of a fossil may be readily determined by the microscope. For those who lack such knowledge and in cases where the replacing mineral is opaque like sulphides, a more satisfactory distinction between open space and replacement is necessary. This may often be made by the position occupied by the included fragments of unreplaced rock. In some animals the original shells, or septae of the original shells, include spaces which are wholly enclosed by shell walls. Where such shell walls are changed into a different material, possibly on account of the superior solubility of the shell material over that of the surrounding and included rock, it is obvious that such a mass of new mineral could not have formed by solution and redeposition, for the solution of the surrounding septum would have removed the support from the enclosed kernel so that it would come in contact with the outside rock mass at some point. Fig. 31 shows this diagrammatically. If the surrounding

FIG. 31.

Diagram to show manner in which cast may be distinguished from replacement in case of fossils altered to ore. K, kernel; K′, position of kernel when shell septum is dissolved out of the rock.

shell mass become dissolved, the kernel K will fall to the position K′ and mineral matter introduced in solution will fill the empty space, leaving an imperfect area of mineral at the point of contact f. If, on the other hand, the new mineral mass is complete it is obvious that the supporting material has at no time been removed and that the process has therefore been one of gradual replacement. No confusion need arise if the shell were hollow and contained no central kernel of rock, as the space would then be completely filled with new mineral and not form a shell around a central core. Fossils therefore whose septae have been completely preserved will often serve as excellent indications of metasomatic processes.

An additional proof of replacement is furnished when fossils have been more resistant than the surrounding rocks so that the rock has been completely changed to ore and the fossil itself left unaffected. J. E. Spurr describes an instance of this kind from Aspen as follows:[24]

"A further evidence of this process of replacement is the finding of fossils which are completely interbedded in the ore, or have been so changed as to form a part of the ore. In a mass of pure native silver, just as it was taken from the ore at the sampler in Aspen, a

[24]Spurr, J. E. Mon. XXXI, U. S. Geol. Surv., pp. 233-234.

perfect fossil gasteropod is firmly embedded, and it is somewhat remarkable that the shell is still made up of the aragonite of which it was originally composed."

It is evident that fossils left in the midst of ore in this way could not have been left unsupported, as would have been the case if the rock had first been dissolved and ore introduced into the surrounding space. The fossil would then have fallen to the bottom of the cavity. The same argument applies when the fossil has been completely changed to ore, provided it is surrounded by masses of ore of the same character and none of the original rock substance left to support it. (This question is still further discussed under the head of unsupported nuclei.)

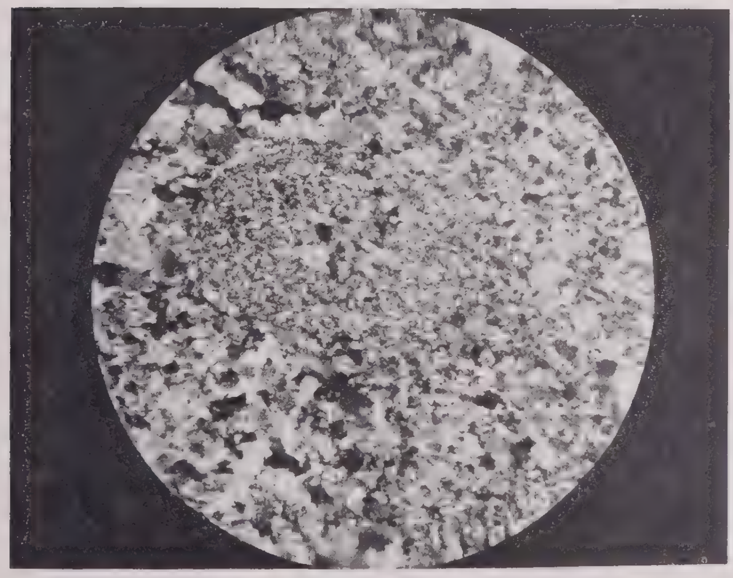
In addition to the larger fossils altered to ore such as may be readily observed in the field, minute microscopic fossils have been retained also. One of the most interesting cases of this kind is that described by H. W. Turner from the Diadem lode, Meadow valley, California:

"A certain portion of the lode is composed of little elliptical bodies which, according to Charles Schuchert of the U. S. National Museum, represent the silicified tests of foraminifera of Carboniferous age belonging to the genus *Loftusia*. The shells of *Loftusia* were originally carbonate of lime."

Fig. 32 is reproduced from this article by Turner and shows the foraminiferal test clearly outlined without the polarizer in the upper slide, the outline seemingly preserved by the unreplaceable impurities of the original rock, which have not been moved from or disturbed in their original arrangement by the alteration of the mass from carbonate of lime to silica. The second figure is the same with the polarizer applied, and shows that the rock is entirely made up of an aggregate of grains of secondary quartz. The different character of the lime carbonate within the fossil resulted in a slightly finer grained aggregate within than without the shell; but the perfect preservation of form is indicated rather by the disposition of the opaque inclusions. Instances in which fossils have been altered into ore by replacement are so numerous that to cite each case is unnecessary.

Rhombic Crystalline Structure of Dolomite.—A few sedimentary rocks only are composed of grains which are distinctly characteristic. In general the grains of sediments are distinguishable as such by their water-worn form only in the coarser varieties of rock, such as conglomerates, and these are composed of pebbles of extremely re-

A



B

Fig. 32.

Thin section of silicified limestone, showing outline of foraminiferal test. *(Loftusia.)* Upper section is with ordinary light, lower with polarized light. (After H. W. Turner, *Jour. Geology.*)

sistant material, such as quartz, quartzite, etc., which resist complete replacement better than the more soluble carbonates. Of the carbonates, the dolomites frequently show a partly crystalline structure, so that when viewed under the microscope they are seen to be composed of aggregates of minute rhombic crystals. Fig. 33, taken from a specimen of shaly dolomite which frequently forms the country rock of the silicious ore in the Black Hills of South Dakota, shows a well developed rhombic structure. Structure of the same kind is quite a striking characteristic of many dolomitized limestones, and an excellent figure of one of them is shown by A. Harker from an English locality.[25] Rhombic structure of this kind is some-

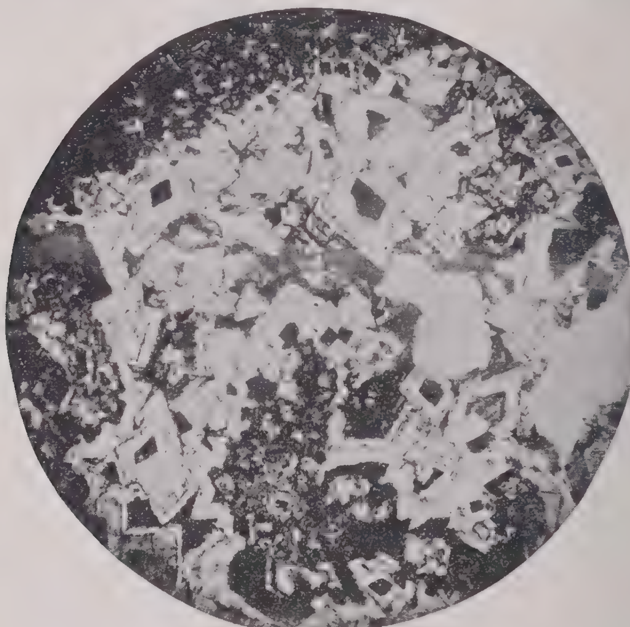


Fig. 33.

Shaly dolomite, showing rhombic crystals of dolomite which constitute the rock, and are shown preserved in silicious ore in plate. A higher power objective is used in this cut than in Fig. 34, so that the rhombs look larger in the figure.

times perfectly preserved in highly silicious ores so that at first glance with a microscope it is difficult to detect the difference between the thin section and one cut from the original rock. An instance of this kind was observed in the silicious orebodies of the Black Hills. This is shown in Fig. 34. In this figure, A, the ore

[25]Harker, A. 'Petrology for Students,' p. 261.

is shown in ordinary light, and the sharp outlines of the rhombohedral crystals of dolomite are extremely clear. In B, the same section is shown in polarized light so that the individual grains of quartz of which the rock is now composed are made evident. The entire rock mass, with the exception of the original impurities in the original dolomite, has been changed to silica, and yet the discoloration due to these minute impurities has sufficed to perfectly preserve the minute original structure.

Phenocrysts.—In igneous rocks the constituent grains possess characteristic forms only when crystal boundaries have been more or less completely developed. The phenocrysts of the porphyritic rocks, and especially the feldspars, are among the most typical structures of some igneous rocks. When such rocks are completely altered by replacement, the original form of the phenocrysts is often perfectly preserved. Little or no confusion of phenocrysts with minerals developed during ore-forming processes can occur, as both orthoclase and plagioclase feldspars rarely develop as the result of ore deposition. I have seen porphyries in Leadville, Colorado, which have been completely altered to silica; but the silica which has taken the place of the phenocrysts is slightly different in color and arrangement from that which has replaced the ground mass, so that the outlines of what were once feldspar crystals can be clearly discerned in the silicious mass. Phenocrysts are often thus preserved when the replacing mineral is silica; but I know of no instances in which replacement by sulphide or metallic ore minerals has resulted in their preservation.

It is important to avoid a confusion of the preservation of the form of phenocrysts in an ore mass with ordinary pseudomorphs after phenocrysts. Thus in the tin ores of Cornwall cassiterite has presumably replaced the large orthoclase crystals of the granite and perfect crystals of cassiterite after orthoclase, that is, having the form of the orthoclase, are found. Although it is probable that these cassiterite pseudomorphs have been formed by the replacement of orthoclase, the process can not be inferred from the cassiterite pseudomorps, for there is nothing in the ordinary[26] type of pseudo-

[26]By the 'ordinary' type of pseudomorphism I mean that type of pseudomorphism by virtue of which one mineral appears in the crystal form of another. There is no doubt in my mind that such pseudomorphs have frequently been formed by metasomatic processes, but I so far disagree with Lindgren and Becker as to believe that the appearance of one mineral in the crystal form of another affords no proof of the action of such a process, unless the new and the old minerals contain some common element and thus indicate chemical change rather than solution and subsequent mechanical deposition.

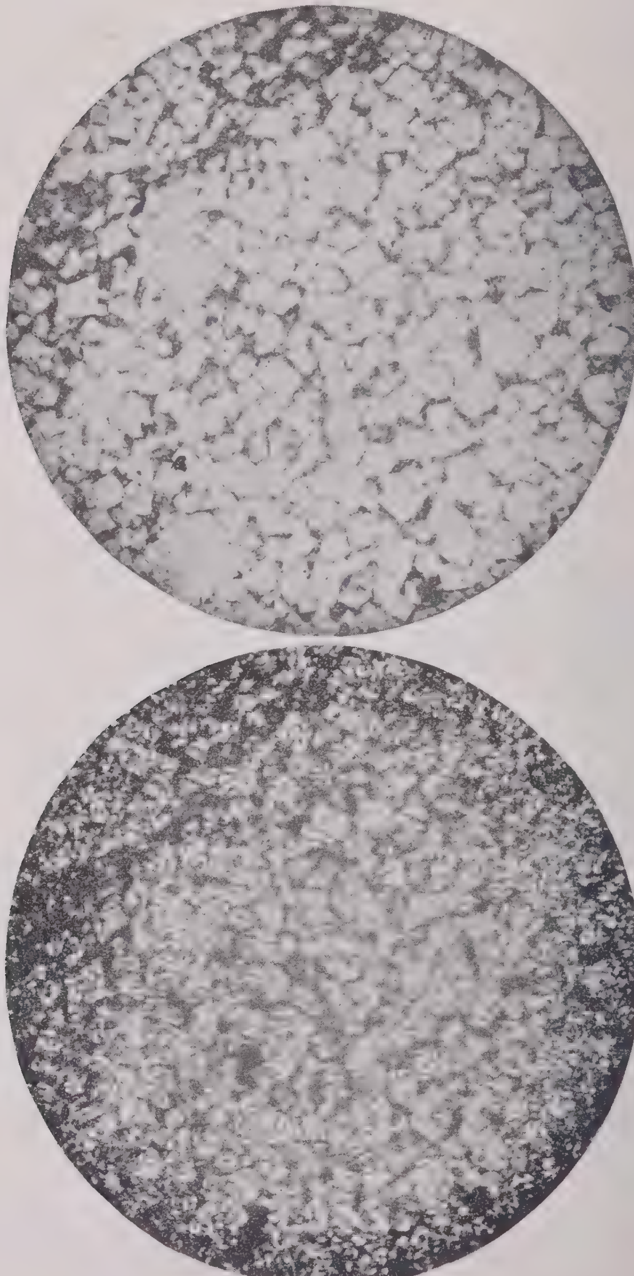


Fig. 34.

Rhombic structure preserved in silicious ore due to replacement of dolomite as shown in Fig. 33.

morphism that will serve as a positive proof of replacement. It is entirely conceivable that these feldspar phenocrysts can have been dissolved out of the granite by vapors charged with fluorine and the space later filled with cassiterite. The form of the feldspar crystals would then have been assumed by the tin ore, and no replacement need have occurred.

SECONDARY ROCK STRUCTURES.

Structures that have been developed in rocks by stress and rupture are often perfectly preserved in orebodies. A few of those that are capable of preservation only have so far been observed; but it is probable that further investigation of replacement masses will in future add greatly to the number now known. Structures of this kind are faults, joints, brecciated structures, and folds, together with metamorphic structures, such as gneissoid structures and schistosity. The first three, joints, faults, and brecciated structures, have so far come under my observation or been noted in the literature. All of these may be developed in orebodies after their formation, so that at first it would appear that some confusion might arise in using them as criteria for the indication of replacement. It is generally possible, however, to follow them from the adjoining country rock into the ore or to detect some feature about their occurrence which will readily determine whether they were present before the ore deposition or have been produced afterward.

Faults.—Small faults often intersect rock masses where mineralization occurs. If the original rock possesses sufficient textural variation such as banding, offsets in the layers or other structures on the two sides of the crack can usually be detected. Mineralizing waters that have gained access through such minute faults have often produced orebodies by replacement on either side of the fissure. Fig. 35 shows a case from one of the mines of silicious ore near Portland, South Dakota, where the offset caused by a small fault is preserved in the ore mass. In this case the ore was evidently introduced after the fault structure was developed, as it is not itself affected by the displacement. There is, furthermore, no break in the continuity of the ore mass, which passes from one side to the other of the former fissure without interruption. Fig. 36 shows the reverse condition where an orebody is itself displaced along a fracture.

Joints.—Joints or intersecting fractures have frequently been preserved in ore masses. Such jointing is distinguished from fissuring described in the previous paragraph by the greater number of the cracks, their occurrence at angles to each other, and the general absence of appreciable displacement along any single crack. They grade into a brecciated structure with the increase in the number of fractures, but may be distinguished from it by the fact that in intersecting joints or stockworks the blocks of rock between

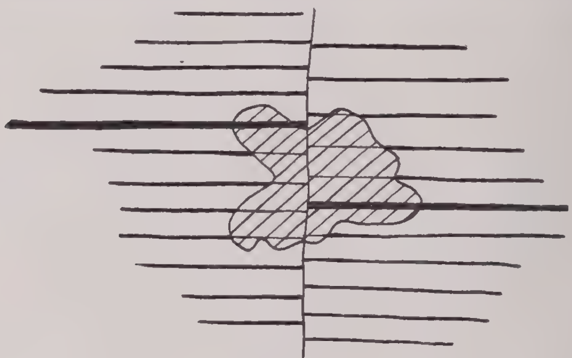


FIG. 35.

Fault preserved in orebody. Orebody itself not faulted, and hence formed after faulting.

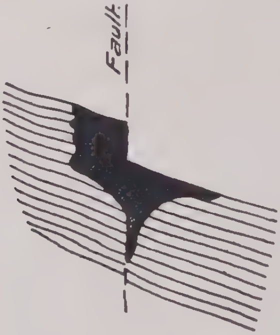


FIG. 36.

Orebody faulted, and hence formed before the faulting occurred.

the fissures have not been appreciably moved from their original position so that banding and other textural peculiarities of the rock pass uninterruptedly across the bounding fissures from one fragment to another. In breccias, on the other hand, the rock fragments have been disturbed by the movement and are set at all angles to each other and frequently lie at considerable distances from the place which they originally occupied.

Intersecting joints are preserved in two different ways: (1) By replacement which has first filled any open space and later proceeded outward from the crack and replaced the included fragments; (2) by the replacement of infiltrated rock-material which has filled the cracks before the ore was deposited. In the former case, rock structures, if any be present, can be traced across from one fragment to the other, although the material is now all ore. It is obvious that such structures could be produced by the shattering of both ore and enclosing rock at the same time, and that without some other evidence would afford no proof of replacement. It usually happens, however, that near the edge of an ore-

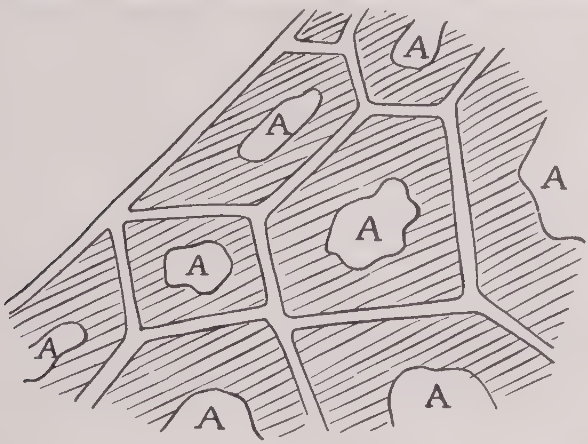


FIG. 37.

Jointed structure preserved in ore. A, A, A, unreplaced cores of country rock.

body fragments have been only partly replaced, so that a central core of original material remains. The original outline of the block is then angular and may be often readily discerned in the ore mass, while the unreplaced core is generally bounded by a wavy, rounded line of demarcation between ore and country rock which bears only a rough parallelism to the outer and angular outline of the block. Fig. 37 will illustrate this point. It is then evident that the mineralization has occurred later than the fracturing, and the jointed structure indicates that the process has been so gradual as not to disturb this original structure. Like other larger structural features preserved in ore masses, however, this is an indication of replacement, but not a definite proof that the process has been molecular.

In the second type of preserved joints the cracks have been sealed up or filled prior to ore deposition and the mass as a whole changed into ore. In such cases the filling material of the cracks in the original rock extends up to the ore mass and the ore itself squarely intersects both filling and the included blocks. The outline of the blocks is preserved by some slight difference in arrangement of the mineral grains which have replaced the filling, and those which have replaced the included rock. In rare instances intersecting filled fissures in original rock masses are filled with material more easily replaced than the country rock which they intersect, and replacement will affect them and leave the included blocks untouched. An instance of this kind is described by Posepny from the jointed limestone masses at Raibl, Carinthia, in which lime partitions have been changed to calamine. These occurrences are interesting; but from the description given it is not evident that the calcite filling the cracks in the original rock has not first been removed in solution and calamine later introduced, and, in my opinion, the evidence is not conclusive.

Brecciated Structures.—Brecciated structures differ only in degree from intersecting joints. When they occur in insoluble and comparatively resistant rocks like granite, gneiss, and quartzite, the openings developed between the fragments are generally not again completely closed, and mineralization begins by impregnation or the filling of the minute cavities. Replacement of the entire mass may then occur; but the structural features and form of fragments are not often preserved so that they can be readily recognized, as the minerals which effect the replacement are more apt to be opaque minerals such as sulphides or metallic minerals. These show the outlines of original rock structures imperfectly, if at all. Unaltered cores in larger fragments may be of service; but as the original outline of the fragment is rarely preserved by these minerals, their relation to the cores cannot be determined, and the criterion fails to be convincing. In limestones replaced by silica it is otherwise. Limestones are often brecciated and the fragments rehealed by later-deposited calcite, so that over extensive areas limestone breccias occur with no appreciable open space developed in them. Breccias of this kind are sometimes replaced by silica and the characteristic structure retained in the ore. An instance occurs in the Carboniferous limestones near Ragged Top mountain in the Black Hills of South Dakota. On the north side of the mountain vertical fissures occur from which solutions containing silica and considerable gold have replaced the limestones for distances of ten, twenty, or thirty feet from the fracture. All of the brecciated fragments are perfectly outlined in the ore as well as the banded structure which crosses them at varying angles. The boundary between ore and fragments is extremely sharp, and the material on one side of the line of demarcation is limestone and on the other silica. All of the structural peculiarities of the limestone remain, and the appearance of ore and rock is so nearly alike that only the slightly darker color of the ore and its greater hardness serve to distinguish it from the adjacent limestone. The fragments are often crossed by the boundary of the ore so that they are composed half of rock and half of ore. In Fig. 9 is shown a sketch of the edge of one of these occurrences. On the south side of the mountain similar orebodies occur; but the replacing material here is a dark-gray mixture of silica and purple fluorite.

INTERSECTION OF ROCK STRUCTURES.

As already stated, replacement ore masses either pass gradually into country rock or cease abruptly, so that there is a sharp line of demarcation between ore and enclosing rock. When the change is gradual, little can be learned by the intersection of structures, and other criteria must be sought; but when the passage is sudden, another and valuable indication of replacement is available. Sharp boundaries of this kind are shown in Fig. 10. All of the structures discussed in the previous paragraphs will then be abruptly cut off by the line of intersection. If the structures are also preserved in the ore, fossils may be found as described by Spurr,[27] or stratification planes, breccia fragments partly altered into ore and continuing uninterruptedly from country rock across the boundary into, and, in the case of bedding planes, through the ore to cross again without interruption into the country rock on the other side. Instances of this kind have been illustrated. The fact that these structures are partly in ore and partly rock proves beyond peradventure that the ores have been produced by a process of substitution such that no disturbance of original form has occurred. The deposition of the ore in an open cavity is shown to be an impossibility.

If the ore is composed of opaque minerals, such as sulphides, the continuity of rock structure is not noticeable, as the structural features are rarely perceptible in the ore itself. The passage of the ore in that case across the original rock structure in a smooth

[27]Spurr, J. E. Mon. XXXI, U. S. Geol. Surv., p. 233.

rounded line, as is the case in some portions of the Leadville ore masses, shows that it has not been deposited in spaces of discission or rupture. The same thing is readily shown by other criteria, such as irregularity of form. The only two possible means by which an intersection of structure such as this can have been produced, are by replacement or deposition in a cavity caused by solution. Considered alone, such intersections are of no great value, as they can easily be explained in other ways; but considered in connection with those criteria which show that the orebody in question has filled in neither a space of discission nor one of solution, they will serve as a useful distinction between masses of sulphides that have segregated from magmas and those that have been formed by later replacement.

ABSENCE OF CONCAVE SURFACES.

It rarely happens that orebodies formed by replacement are confused with those which have filled openings caused by fissuring or the rupture of rock masses, that is, with what have been termed by Posepny spaces of discission. The edges of cavities of this kind are often jagged, and the forces which produce them cannot in any case give rise to spaces which possess the extremely irregular boundaries of many replacement orebodies. With open spaces formed, however, by the solution of the country rock, whatever be its lithologic character, and the later formation of ore masses by deposition in them, there is sometimes difficulty in making the distinction. When the line of demarcation between ore and country rock is sharp and the transition abrupt, some light is thrown on the matter by the examination of solution cavities. In almost any region where limestone forms the country rock, but especially in the East where atmospheric waters are heavily charged with acids, limestone suffers greater erosion by solution than by mechanical disintegration. In almost any limestone outcrop in the Eastern States or on the surfaces of fragments long exposed, the rock may be seen pitted by bowl or saucer-shaped concave depressions, which are usually of greater diameter than depth. Between them the separating ridges are often sharp, though sometimes slightly rounded. So common a feature of limestones exposed to atmospheric agencies is this that one comes to make unconscious use of it in the rapid recognition of limestone outcrops. In limestone caverns the same thing is perceptible, although it is often rendered more obscure by the enlargement of a cavern by the falling in of portions of the roof. In all cases, then, of the solution of large caves in limestone such concave surfaces are noticeable and greatly preponderate over the convex. That cavities may be formed by solution in which this feature is not readily distinguishable must be admitted; but if an opening shows them as one of its striking characteristics it would be most reasonable to attribute it to solution. An admirable illustration of this form of solution surface is shown by F. L. Ransome in the gypsum bodies in the Enterprise mine at Newman Hill, Rico, Colorado. A careful examination of

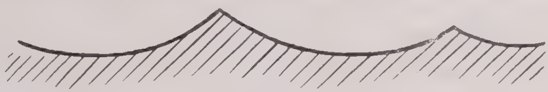


FIG. 38.
Concave depressions produced by solution.

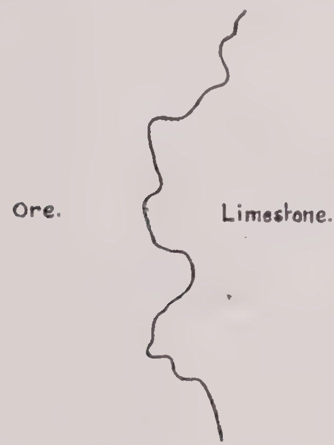


FIG. 39.
Concave-convex depressions produced by replacement.

any limestone caverns will, I think, convince the reader of the preponderance of such concave surfaces. Replacement orebodies rarely if ever (so far as my observations go), show such intersecting concave surfaces. Fig. 38 shows a concave surface produced by solution. Fig. 39 shows the characteristic type of boundary between ore and rock in a replacement mass. Concave surfaces of this kind are chiefly confined to limestone; but in the open caverns considered to have been produced by solutions in the quartzite of the American Nettie mine near Ouray, Colorado, they may be also observed.

ABSENCE OF CRUSTIFICATION.

In many epigenetic deposits of minerals, whether they be metalliferous or non-metalliferous, when formed in an open space the minerals are deposited in successive layers on the walls of the space. Changes in the character of solutions or fractional precipitation from a single solution has caused unlike layers to be deposited upon one another. In the most perfect instances the form of the outer surface (or wall-rock side) of each layer is determined by the surface upon which it is deposited; but the upper surface (surface toward the empty space) being free to develop, exhibits crystalline faces of the component minerals. A succession of mineral crusts is found xenomorphic on the wall-rock side and crystalline on the inner or empty-space side. The successive crusts cover both walls and all fragments of rock which are within the cavity. When the open space is completely filled the two corresponding innermost crusts come in contact and a perfect crustified deposit is formed. If the process is arrested before completion, or if widenings of the opening cause its incomplete filling, the innermost surfaces of the latest crust will be covered with druses of crystals which project into the central opening or vug. Mineral crusts of this kind vary a little in thickness, but in general they show a remarkable uniformity of thickness, and of course faithfully follow the contour of the surface on which they are deposited. Such structures when met with in fissure veins are often termed 'comb structures,' owing to the frequent occurrence of quartz crystals arranged with their longer or *c* axes perpendicular to the surface of the opening. They are not alone characteristic of fissure veins. Wherever ores develop in open spaces they are apt to form. They are never formed by replacement, though they are sometimes confused with banding produced in that way. It is not necessary here to enter into the causes which produce irregularities and lack of symmetry in such layers, as these do not immediately concern the question of replacement. F. Posepny was, of all the writers on ore deposits, probably the most strongly impressed with the importance of these layers, and to him is due the term 'crustification' proposed to describe them. The following passage will serve to illustrate the importance which he considered them to have.[28]

"With regard to the filling, I observe, first, that the mineral deposits upon the walls of cavities, from liquids circulating within them, usually have a characteristic structure, for which I pro-

[28] Trans. Amer. Inst. Min. Eng., Vol. XXIII, p. 207.

pose the name 'crustification,' as a companion to 'stratification.' * * * Most frequently mineral crusts occur concentrically in regular succession and fill the whole cavity (except the central druse), thus forming a symmetrical crustification. They cover, however, not only the cavity walls, but the surface of every foreign body in the cavity, thus forming crusted kernels which greatly complicate the phenomenon. * * * As a general rule, however, *crustification is a characteristic feature of cavity filling.*"

Both J. A. Church[29] and G. F. Becker[30] have objected to the emphasis that Posepny has laid upon crustification as a means of diagnosis of cavity filling, because, as they assert, it may be so exactly simulated by metasomatic processes that one cannot be certain of the origin of the structure. If the matter be examined carefully it seems to me that these difficulties disappear, and I am strongly in accord with Posepny as to the utility of this criterion. It further seems that the differences of opinion have arisen from an inadequate exposition of the exact nature of crustification and too inclusive a statement of the conditions under which it may be used—also because of the attempt of Posepny to detect evidences of 'crustification' in the descriptions of ore deposits which he had not seen. Crustification is characteristic of many cavity fillings; but not all. Many fissure veins occur which are completely filled by minerals, for instance with galena, in which no deposition in layers is discernible, and yet which, from the angular nature of the walls and the manner in which the inequalities of the two opposite walls fit into one another, cannot be attributed to other than the filling of cavities. Lenticular masses of quartz in schist and similar types of vein material frequently show no crustification. In this latter case it is improbable that cavities stood open at the time of the introduction of the quartz or other mineral in them; but it seems likely that they represent the *loci* of minimum strain and that solutions under considerable pressure deposited mineral matter in them *pari passu* with their formation. They are therefore not characterized by crustification nor are they formed by replacement. I therefore believe that crustification (that is, the true crustification described below), if present is a definite evidence of the formation of ores in an open cavity—but its absence by no means indicates that a deposit has been formed by replacement.

If a deposit, therefore, is truly crustified, it may be safely con-

[29] Trans. Amer. Inst. Min. Eng., Vol. XXIII, p. 596.
[30] Trans. Amer. Inst. Min. Eng., Vol. XXIII, p. 603.

sidered a cavity filling; if it is not crustified other criteria must be applied. True crustification may not be in all cases distinguishable from banding produced by other causes; but such cases are not of very frequent occurrence. If mineral is deposited on the walls of an opening in layers, each crust may have a crystalline druse on one side and be adjusted to the form of the underlying crystalline druse or the irregularities of wall rock on the other. Such relations are not, so far as I am aware, to be observed in metasomatic deposits; although crustified linings are found in vugs caused by the decrease in volume of the original rock during transformation. The rock-side extremities of the crystals do not then rest upon the upper crystalline surface of layers formed below, but interlock with the grains of similar metasomatic mineral which compose the ore. Indeed it is often possible in this way to distinguish minerals, by the relation of their under surfaces. It often happens that volume vugs are filled either with the material dissolved from the bed-rock during the process of replacement, or with minerals actually deposited by the ore-bearing solutions. Such minerals either form well defined crystal faces on their upper surfaces, and no faces on the lower, or completely fill the volume vug and have their form entirely determined by the crystalline druse lining the cavity. Calcite, jarosite, and fluorite occur in this relation in the Black Hills silicious ores. They are cavity fillings just as truly as those which occur in any pre-existing opening.

In many cases crustification in a cavity filling is imperfect; that is, the periods of precipitation of the different crusts so overlap that instead of each resting upon the crystalline surface of the next below, the minerals are intermingled at the junction, and are consequently more or less xenomorphic in their boundaries. This is particularly common in banded veins of sulphides where fractional precipitation is such a common process in the origin of the layers. In such cases their discordance with the stratification of the enclosing rock will show that they do not represent sedimentary banding (see Fig. 29, p. 263). The preservation of the regular order of succession about included rock fragments or the existence of angular druses caused by angular spaces between fragments lined with druses will serve to distinguish them.

The most difficult cases to distinguish are those of replacement veins and filled fissures. Fissure veins are often caused by a multitude of minute fault fissures extending over a width of five or ten or more feet; that is, are formed by sheeted zones. In these the space for actual deposition is small and the veins are often formed by the replacement of the tabular masses of rock that lie between the fissures. Usually the mineral formed by the replacement of rock from one fissure will then coalesce eventually with that arising from the next adjoining fissure and the arrangement and material may be slightly different in the two cases, so that when the process is complete there will be bands of replacement mineral which will simulate with extreme closeness the imperfectly developed crustification arising from fractional precipitation in a cavity. In some instances such cases are extremely difficult to distinguish, and search must be made in the vein for angular fragments of included rock which have been incompletely replaced. If such fragments show a perfect angular form underlying the outermost mineral crust, even though they may be almost completely altered by vein-forming waters, they will suffice to show that the crusts were formed in an open cavity. The phenomenon of crustification may be carried down to microscopical determinations and definite crusts detected of a very minute character. Lindgren[31] has described one such instance from Cripple Creek, where spaces of dissolution in granite are shown to have been filled by crustified lining of quartz.

UNSUPPORTED STRUCTURES.

Residual Nuclei.—In nearly every orebody that is formed by replacement, there are likely to occur irregular masses of country rock or 'islands' which have escaped mineralization. These may be of the same rock as that which encloses the ore or of a different rock, such as a porphyry intrusion, shale band, or grains of insoluble mineral which were present in the country rock prior to mineralization. In the first instance they have remained unaffected either because the channels of access are so distributed as to render them less easily accessible, or because some seemingly fortuitous causes have diverted the flow of mineralizing solutions in other directions; in the second because their relatively resistant chemical nature has prevented their mineralization. In many cases these masses or 'islands' are supported; connected with the country rock above and below or to one side, and they then furnish no serviceable indication of the action of replacement. Such instances may be seen in the plans of ore-shoots on Fig. 1 and are noticeable in nearly every underground map of a replacement ore mass. In other cases it happens that not only has the country rock on all sides

[31]Trans. Amer. Inst. Min. Eng., Vol. XXX, p. 631.

been replaced, but also above and below the mass, so that the area of unmineralized rock is completely separated by the surrounding ore from the mother rock of which it was once a part. It is obvious that in any open space, whether formed by chemical action or mechanical rupture, masses of rock could not have remained suspended in mid-air until such time as ore was introduced to afford them a means of support. In order that they can have been left undisturbed in the heart of an ore mass some process not involving the removal of structural support must be conceived. Molecular replacement by the gradual nature of its progression offers a complete explanation of these masses.

If solution and redeposition be believed to have caused them, it must have involved the widespread solution of small cavities and their subsequent filling, then a new solution of more cavities and more filling, and so on until the entire mass of rock was changed into ore. The process of solution must always have been arrested just short of the removal of adequate support and remained in abeyance until sufficient ore had been introduced to allow the safe removal of more rock. Furthermore, with each renewal of deposition the character of depositing solutions must have been of the same chemical nature. While such a careful observance of structural safety would be a *sine qua non* to an architect or engineer, it is difficult to believe that it can reasonably be attributed to mineralizing solutions. Under these circumstances unsupported nuclei, while they cannot be regarded as proofs of the molecular nature of the process, approach so closely to absolute proof that they render this criterion of great service. This is the more important as such structures as this are often large, easily observed, and not at all uncommon. In distinguishing filled fissures from replacement veins this criterion is of less value because fragments of the walls are there so often forced away from the walls by the growing crystal crusts.

Added force is given to this criterion when the replaced rock is a sediment by the conformity of the stratification in the isolated mass with that of the country rock beyond the ore—showing that the mass is in its original position and has not been moved by crystal growth or any other cause during the formation of the ore. This is illustrated in Fig. 40. Fig. 41 shows the conditions which would probably occur in a filled cavern, where pieces of country rock have fallen to the floor and where the strata in them have all angles to that of the surrounding rock.

• In the second case mentioned, that is, where the isolated mass of unsupported rock is of a different nature from the surrounding rock, the comparatively resistant nature of the rock material has caused it to remain either unaffected by mineralization or only slightly

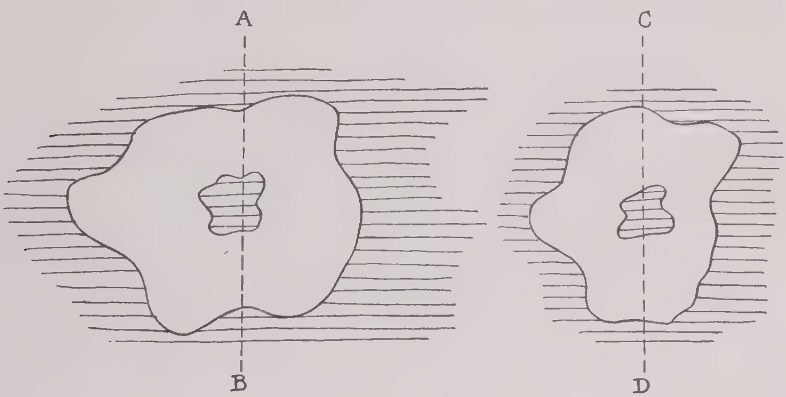


FIG. 40.

Section on A B. Section on C D.

Diagrammatical sections of hypothetical orebody in limestone beds with completely unsupported nuclei of original rock entirely enclosed in ore. Stratification of the 'islands' shows that the limestone masses have not been removed from their original position.

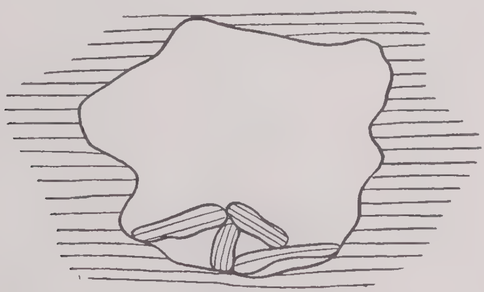


FIG. 41.

Conditions which would exist in case an empty cavern had been filled with rock débris. This would appear at the bottom of the ore-mass. Also stratification in the débris at varying angles to its original position in the country rock.

affected. Three instances of this kind can be readily cited. (1) Original quartz grains in the Black Hills refractory silicious ores; (2) porphyry masses in the sulphide ores of Leadville, Colorado; (3) thin shale bands in the ores of the Black Hills and at Leadville, Colorado.

1. In the country rock of the Black Hills silicious ores (a magnesian limestone, usually slightly marbleized) isolated grains of sand frequently occur. These have presumably been derived from some igneous rock, as they are filled with minute gas and other inclusions and may easily be distinguished from the clear secondary silica which composes the bulk of the silicious ore. They can only be seen, of course, with the microscope. They occur scattered all through the ore, just as in the limestone, and *not* at the bottom of the ore mass, as would have been the case if the ore filled a solution cavity. Nor do they occur in clusters as might be the case if the ore was made up of coalesced masses formed in small solution cavities.

2. Most porphyry masses are well supported, but in the large ore masses of Leadville irregular bodies of porphyry now completely changed to clay occur in the heart of the orebodies often connected with the main porphyry intrusion by so narrow a neck of material as to show that they could not have remained unsupported if the ore had been deposited in an open cavity.

3. In the country rock of the silicious ores of the Black Hills the bands of easily replaced dolomite are sometimes separated by beds of aluminous shales, extremely resistant to mineralization. These are often extremely thin down to $^1/_{16}$ of an inch in thickness, and yet they run for great distances through the ore, often passing completely through it. They continue in many cases over areas of hundreds of square feet or more. If these ores were originally formed by the filling of cavities the intervening lime beds must have been completely dissolved out, leaving the shale bands as a sort of 'grizzly' supported in perfect equilibrium and without the slightest disturbance over great areas. It is therefore evident that the process of replacement must have operated in these masses, as that is the only method of deposition by which the rocks could have been changed to ore and support at no time removed. The same characteristics can be noted in some Leadville orebodies. Those which occur in the Blue or Carboniferous limestone and in the upper White limestone do not show this feature, but at the base of the White limestone where it passes into quartzite the limestone is interrupted by many highly aluminous porcelain-like beds of shale, and where these beds have been replaced by ore, the shale bands have remained unaffected within the ore mass. This is especially well shown in the lowest ore mass in the Tucson mine on Iron Hill where the shale beds remain unreplaced in much of the ore mass.

Fossils.—J. E. Spurr has described a fossil from the ore of Aspen, Colorado, already mentioned completely surrounded by ore; but not itself replaced. It is obvious that this fossil could not have remained unsupported in mid-air any more than the other structural masses mentioned above.

Phenocrysts.—When porphyritic igneous rocks are replaced the phenocrysts are sometimes more resistant to replacement than the body of the rock and sometimes persist in the ore as soft, whitish, clay-like crystals with original form unimpaired and substances only partly affected by mineralization. It must of course be remembered that in a rock other than limestone the process of replacement is frequently incomplete, that it affects only some of the minerals of the rock. Solutions could, therefore, have easily dissolved and removed some of the minerals of the rocks and left a matrix which was porous but perfectly supported into which ore was later introduced. This of course would not be replacement, but simply solution and redeposition. In order that phenocrysts should furnish, as unsupported nuclei, a definite indication of replacement, the change from rock to ore must have been so complete as to leave none (or extremely little) of the original substance to support the crystals. Phenocrysts are much more significant when preserved in ore than as unsupported nuclei.

Earlier Formed Crystals in the Ore.—Many sulphide ore masses show complete crystals of quartz pyrite, galena or some other mineral perfectly bounded on all sides and now completely surrounded by either a second generation of the same mineral or other ore minerals. Lindgren gives two illustrations of thin sections of silicified limestone from the Elkhorn mine, Montana, which illustrate this point. In the first of them quartz crystals are seen developing in the limestone. In the second such quartz crystals are also seen in outline with all of the intervening lime replaced. They are not clustered together at the bottom of the ore mass nor supported by contact with contiguous crystals; but now stand off by themselves and are an excellent case of unsupported structures.

The silicious ore of the Black Hills often contains perfect crystals of pyrite. The jasperoid masses (masses of secondary silica) of the Ibex mine in Leadville often show complete crystals of pyrite imbedded in the silica. Many replacement orebodies show honeycombed quartz at the surface with cavities having the form of pyrite crystals which have been dissolved out by oxidation process. Instances of this kind from sulphide orebodies are too numerous to need separate mention. It is evident that these perfect imbedded crystals were either formed first and existed as replacements in the country rock or were formed later. If later they must have replaced the ore mass itself. It seems probable, at least in limestone masses where the country rock is so much more soluble and easily replaced than the ore, that they represent the first mineralization, replacing the country rock as a sort of advance guard of the main mineralization. The rest of the rock was then replaced, leaving these earlier replacements completely surrounded by ore. In this case they serve just as other unsupported structures do to prove the gradual nature of the substitution of ore for rock. If they were introduced later they could not have been formed by any process except replacement of the ore itself, for they are perfect crystals on all sides and show no evidence of having had a supporting surface upon which to grow. If both complete crystals and enclosing ore are of the same mineral, the complete crystals are even more certainly the earlier replacements. When, for instance, perfectly formed pyrite crystals are imbedded in finer grained pyrite, as in Leadville, it seems chemically improbable that a mineral should have replaced itself. In any case they show that either they themselves were formed by replacement, or, on the other hand, that the surrounding mass of ore has been formed by that process.

Care must be taken in using this criterion to distinguish between the nearly perfect crystals that one sees in crustified or imperfectly crustified linings of cavities whose interstices have been filled with other deposits from solution and the perfectly formed crystals which occur in masses of ore. Generally, evidence of some imperfect face, where growth on a wall has occurred, can be found, or if not, then the evidently crustified nature of a deposit will make the origin of the seemingly perfect crystals manifest. Confusion might also occur with igneous orebodies formed from magmatic segregation. Such are supposed by some authors to be the nickeliferous pyrrhotites. Generally the nature of the ore occurrence will be such as to show whether or not it may be ascribed to magmatic segregation and this point once settled the criterion becomes again available.

FORM AS A CRITERION.

As a criterion for the recognition of ore masses produced by replacement, form, while it will not serve as a sufficient proof in itself, will form a strong *a priori* argument for this origin. A glance at any of the illustrations of replacement bodies in limestones will serve to prove beyond doubt that cavities of such shape could not have been produced by any mechanical process. Rupture, faulting, and fissuring of rock could certainly not have produced them. The only remaining process then to which irregular openings of such kind can reasonably be attributed is solution. If it be possible to conceive of waters first dissolving out great caves in limestone or in rocks of greater resistance to solution openings of this kind might be thought to have been formed. An examination of any limestone cavern will furnish cavities whose irregularity of form, distribution, relation to fractures in the rocks, etc., resemble to some extent replacement orebodies. It was for this reason, indeed, that early opinion[32] attributed all such irregular masses in limestone to the filling of caves formed by surface waters. There are many facts which show this solution and re-deposition to have been impossible. The first argument advanced was that ore deposits, such for instance as those at Leadville, Colorado, were formed at a geological age when a very heavy covering of still uneroded rock lay above the rocks which now enclose the orebodies. The depth of cover in Leadville is estimated at 10,000 ft. Surface waters do not form caves below the level of permanent ground-water so that their formation in such a manner could not have occurred unless depression to great depths occurred afterward and evidence against such depression is overwhelming. Further evidence is afforded by the fact that many of the minerals which occur in such orebodies are stable only under the high pressure and temperatures that obtain at depths very far below the level of permanent ground-water.

If then open cavities have been formed and later filled with ore, the solution must have been performed by uprising mineral waters, presumably different waters from those which deposited the ore masses themselves. Posepny[33] was of the opinion that mineral waters have in many cases dissolved out such openings, and even supposes them to have forced their way upward through rock masses without the aid of any channel of access. In the majority of ore deposits now ascribed to replacement the other criteria, unsupported nuclei of limestone, or other original rock, the original sand grains of the rock, the formation of perfect crystals of one or more minerals in the ore now surrounded entirely by ore, preservation of structure, etc., have one or all shown beyond peradventure that the orebodies could never have been formed in open cavities. There are, however, some few cases in which the hypothesis advocated by

[32]Arnold Hague. 'Geology of the Eureka District, Nevada,' U. S. Geol. Surv., Mon. XX, pp. 308, 311, 316.

[33]Trans. Amer. Inst. Min. Eng., Vol. XXIII, p. 216.

Posepny seems true, for crustification of minerals on the walls of irregular cavities conclusively proves that the process was one of solution and later deposition. The lead-zinc ores of Wisconsin (see Fig. 29), described by T. C. Chamberlin, are instances of this; the ores of Rezbanya, described by Posepny; in part the gold ores in the American Nettie mine in Ouray, Colorado; all these represent such an occurrence. Solution and redeposition are also described by Lindgren and Ransome at Cripple Creek. In the upper oxidized portions of any ore deposit in soluble limestone where surface waters can penetrate, open caves lined with crustified oxide ore are often found. They occurred in Eureka, Bisbee, and are even described by Blow from Leadville; but in none of the sulphide masses can any such occurrences be noted. Another very strong argument against the formation of these large irregular masses of ore as fillings of solution caves in limestone is the absence of cave detritus in the orebody. In any incompletely supported cavern, fragments of the rock forming the roof fall from time to time and an accumulation of débris occurs on the floor of the cave. This is heaped up in an irregular manner, the bedding planes lying at all angles, according as the fragments rest after their fall. Such detritus was actually found in the cave deposit of the Copper Queen mine where caves, formed by surface waters in the upper workings, occurred lined with crusts of malachite and azurite. But in none of the large orebodies that have come under my observation or in any whose description I have read can such detritus, gathered at the bottom of the ore masses be observed. Fig. 40 and 41, page 287, are diagrams illustrating this point.

In conclusion, then, it may be said that irregularity of form, unless the ore mass shows a definite crustification on the walls, or unless distinct intersecting concavities be observable, is in itself, a very strong, though not necessarily conclusive, proof of the formation of an ore mass by replacement.

CAVITIES LEFT BY DECREASE IN VOLUME.

It rarely if ever happens that material substituted for country rock is of equal volume with the original material. The varying densities of minerals and proportions of the new and old minerals taking part in the reactions, usually result in a very marked change in volume. Lindgren has shown that formulae for certain rock alterations may be written indicating both increase and decrease in volume. It is difficult to conceive how a mineral of greater volume than that replaced can be introduced without a marked compression of the adjacent mineral grains, and such pressure should, if present, show under the microscop in wavy extinction and other recognizable optical anomalies. These have never, to my knowledge, yet been detected, and it might therefore be supposed that increase in volume of actual substance has not occurred. Where porosity of original rock, however, is large, a mineral of greater volume might be conceived to form by the occupation of all the available pore spaces. Replacement might therefore easily occur in porous sediments when a considerable increase in volume was involved without producing strain phenomena in constituent minerals of the rock.

A decrease in volume involves no difficulties, and may find expression in a porous rock as a result of the substitution of minerals of greater for minerals of less density. Thus, if in a limestone of 3% porosity galena be substituted for calcite, and actual measurements of volume of the resulting rocks show a porosity of 30%, a decrease in volume of 27% has occurred. If the molecular volumes of the minerals which are often substituted for limestone be examined and compared with those of the component minerals of the replaced limestone it will be found that the molecular volumes of the new mineral are sometimes less and sometimes more than those of the original rock. This is shown in the table given below.

Minerals in limestone.		Specific gravity.	Mol. weight.	Mol. volume
Apatite	$3CaP_2O_5.Ca(Cl,Fl)_2$	3.22	501.22	135.7
Kaolinite	$H_4Al_2Si_2O_9$	2.5	259.05	103.62
Glauconite	$Fe_9K_5AlSi_3O_{34}.(OH)_3$	...	.....	.....
Carbon (graphite)	C	2.09	12.0	57.41
Magnetite	Fe_3O_4	5.0	224.06	44.81
Calcite	$CaCO_3$	2.72	100.07	36.78
Rhodochrosite	$MnCO_3$	3.7	134.99	36.48
Siderite	$FeCO_3$	3.9	116.02	29.75
Magnesite	$MgCO_3$	3.0	84.28	28.09
Quartz (igneous)	SiO_2	2.2	60.4	27.45
Rutile	TiO_2	4.25	80.15	18.06
Minerals in ores.				
Stibnite	Sb_2S_3	4.25	337.07	74.35
Gypsum	$CaSO_4.2H_2O$	2.32	172.17	74.21
Barite	$BaSO_4$	4.72	233.5	49.41
Scheelite	$CaWO_4$	6.0	288.9	48.15
Chalcopyrite	$CuFeS_2$	4.3	183.76	42.73
Wolframite	$FeWO_4$	7.5	304.85	40.64
Galena	PbS	7.7	238.99	31.04
Arsenopyrite	FeAsS	6.27	163.1	26.01
Sphalerite	ZnS	4.0	97.48	24.37
Fluorite	CaF_2	3.25	77.89	23.97
Quartz (vein)	SiO_2	2.6	60.4	23.23
Pyrite	FeS_2	5.2	120.16	23.11

In cases where the molecular volume of the new mineral is a little less than that of the mineral replaced, it is obvious that if an equation be assumed for replacement involving only the substitution of one molecule of new mineral for one molecule of original rock, a slight decrease of volume would result. It frequently happens, however, that the replacing mineral shows a much less or much greater decrease in volume (as shown by the volume vugs or cavities in the replacing mineral) than is called for by this difference, and it is quite evident that the equation assumed for the change may involve different numbers of molecules on its two sides. This is especially evident when a mineral like quartz replaces limestone, and the vugs or cavities left in the resulting material are in greater abundance than the difference in molecular volume would seem to justify. Again, it is frequently the case that the molecular volume such as that of wolframite is greater than that of the original mineral, and yet a very marked decrease in total volume has occurred. This is seen in wolframite deposits of the Black Hills, South Dakota, which replace limestone. Lindgren[34] has shown in great detail how the nature of the equation will affect the change in volume theoretically calculated. It is furthermore impossible to calculate this change exactly from analyses, unless some one element has persisted unchanged in the process, which does not often happen. The observed facts, however, whatever may be the theoretically calculated change, show that in nearly all silicious replacements and in by far the greater number of metallic replacements there has been an appreciable and often very marked decrease in the volume of the rock. This finds expression in widely distributed cavities in the ore into which crystals of the latest formed ore minerals project. These cavities are usually without regular form or orientation, having all possible forms and being set at any angle to the original rock structures and to each other. They are frequently of extremely intricate form, being almost labyrinthine in their complexity. Such a reduction in volume is further borne out by the fact that in most cases the *total space* occupied by the new material is of exactly the same size as before alteration. That is, the rock mass itself has not been condensed into a smaller space. Thus in Leadville the rock structures, stratification, and porphyry limestone contacts are not at all disturbed during mineralization. Likewise in the silicious ores of the Black Hills the strata run directly through the ore, and where two unmineralized layers run through the mineral mass without silifica-

[34]Trans. Amer. Inst. Min. Eng., Vol. XXX, p. 591.

tion the shale bands are no nearer together nor farther apart than before the replacement. This is illustrated in Fig. 11 and 42.

Pores of this kind, or 'volume vugs,' are often of great value in detecting replacement. They cannot be, of course, regarded as very serviceable criteria in determining the molecular nature of the process; but they are frequently so characteristic a feature that they will lead one to look for other criteria of a more certain

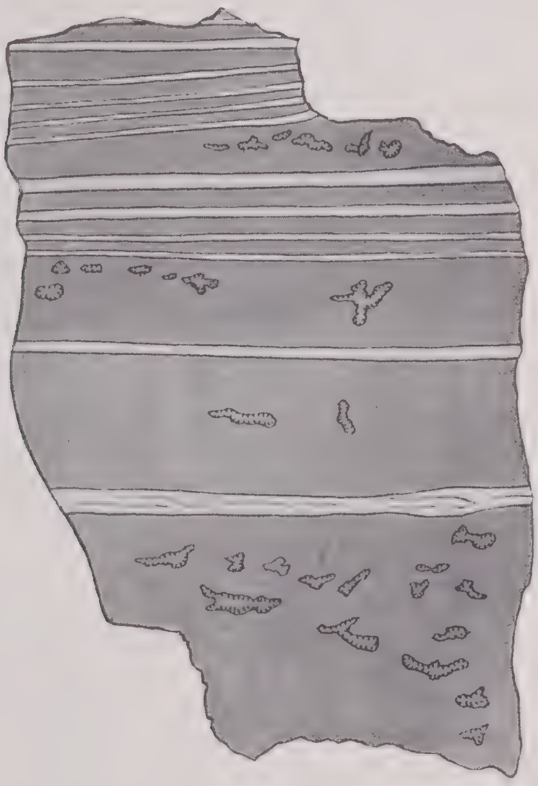


FIG. 42.

Shale bands persisting in silicious ore formed by replacement of alternating dolomite and aluminous shale bands, Portland mine, Portland, South Dakota. Two-thirds natural size. The white bands are unaltered shale layers. The dark spots are cavities left by decrease of volume.

character. It is important that they should not be confused with interspaces between crustified layers which line cavities. When mineral crusts are very definite, there is usually no difficulty; but when crustified layers are imperfectly formed, the relation of the openings to fragments of country rock should be determined.

Volume vugs are much more irregular in shape than cavity vugs, are rarely if ever angular in outline, are generally more intricate, and bear much less definite relations to wall rock, included fragments, etc., and are usually the more widely disseminated in an ore mass. In some instances the distinction is difficult to make, and this criterion then fails; but in the majority of cases the origin of the openings is at once evident.

EXCESS OF VOLUME OF NEW MINERAL OVER PORE SPACE OF COUNTRY ROCK.

In many dense igneous rocks disseminated particles of ore are introduced in the vicinity of a fissure opening. It may be an easy matter to determine whether they are epigenetic or igneous in origin; but the distinction between impregnations, that is, particles of ore deposited in original pore space, and disseminated replacements, is more difficult. In such cases, if the average porosity of the country rock be determined and then the total volume of the new mineral be determined, if the volume of the new mineral is in excess of the available pore space, some of the rock matter must have been removed to make room for it. This, of course, gives no clue as to whether such increased space was caused by replacement or by the formation of minute and widely scattered spaces of dissolution; but it will serve to direct the investigation toward the discovery of those criteria which will determine this particular distinction.

Physical Conditions Under Which Replacement Can Occur.

It is not my purpose to enter into a detailed discussion of the chemical problems of replacement, but it is necessary to descride briefly the different physical conditions under which it may occur in order that some of the more complicated cases, involving contact metamorphism and the consequent complex changes in volume of the resulting mineral masses, may not give rise to confusion.

Replacement has been brought about unquestionably by the substitution of mineral matter in solution for mineral matter in the solid condition, the process involving both the removal of the original material and the deposition of the new. This mineral matter in solution may be introduced into the rock under four different conditions:

1. The mineral matter may be in solution in surface waters which have dissolved it from the upper portion of a deposit and

carried it downward through cracks and fissures. It is then under low pressure and at surface temperatures except in so far as the heat of chemical reaction raises the temperature during the process of replacement. Replacement by secondary oxides and much secondary sulphide enrichment are believed to have been produced in this way.

2. It may be in solution in sea water or water of lakes and streams, and may replace soluble carbonates which are accumulating on the bottom. It is then cold; or, more exactly, at ocean or surface temperature. Mineral matter in this form of solution is supposed by C. H. Smyth, Jr., to have been responsible for the formation of the Clinton iron ores.[35]

3. It may be in solution in so-called 'juvenile' waters which are hot ascending waters and to which the bulk of normal ore deposits, usually termed hydrothermal deposits, are, in my opinion, to be attributed. Solutions of this kind are probably highly heated and under considerable pressure, but are below the critical temperature and pressure of water, and consequently aqueous. They operate under conditions of temperature and pressure insufficient to produce contact metamorphism. Such hydrothermal replacement is supposed to have produced such deposits as those in the Black Hills, at Leadville, Colorado, and possibly at Eureka, Nevada.

4. It may be in solution in water which has been raised above the critical temperature and pressure so as to be in a vaporous condition. Such solutions are presumed to arise as emanations from magmas. They are not only hot themselves, but they operate on highly heated rock masses. They arise chiefly in the neighborhood of intrusive igneous masses. If limestone or calcareous rock is present, their action is supplemented by intense contact metamorphism and rendered excessively complex by volume changes which are independent of simple metasomatism. If limestones are absent, they produce deposits commonly called pneumatolytic deposits. It has been possible to identify deposits formed under some of these conditions by means of the minerals which compose them. The studies of Doelter, Lindgren, Wright, Königsberger, and W. H. Emmons have assisted in the determination of the characteristic temperatures and pressures at which various minerals may form and at which they later suffer inversion to other crystal forms. By a thorough study of the mineralogy of a deposit, therefore, we are often able to determine the probable approximate temperatures and

[35]This volume, pp. 33-52.

pressures of its formations. These in turn help in determining the geological conditions under which orebodies have presumably originated.

CLASSIFICATION OF REPLACEMENT DEPOSITS ACCORDING TO PHYSICAL CONDITIONS.

These conditions of solution may be expressed in terms of the following classification:

Replacement.	*Thermal.* (By solutions at elevated temperatures greater than surface temperatures.)	1. Pneumatolytic replacement (by solutions at temperatures and pressures greater than critical temperature of water).	*a.* Contact metamorphic replacement. *b.* Pegmatitic replacement apart from contact metamorphism.	Primary
		2. Hydrothermal replacement (by solutions at temperatures and pressures less than critical temperatures of water).		Primary
	Athermal. (By solutions at low temperatures at or less than surface temperatures.)	3. Contemporaneous replacement (by seas, lakes and streams during deposition).		Primary
		4. Surficial replacement (by descending meteoric waters).	*a.* In the form of oxides. *b.* In the form of secondary sulphides.	Secondary

Pneumatolytic, hydrothermal, and contemporaneous replacement are primary processes, that is, they have operated to form orebodies previous to the action of superficial alteration or change. Surficial replacement is entirely secondary.

The criteria for the recognition of replacement which have been discussed in the preceding pages apply only in minor degree to contact metamorphic types, and are mainly concerned with the hydrothermal group of deposits. The consideration of the other and more complex forms of contact metamorphic replacement is reserved for fuller discussion in a more detailed paper now in preparation.

OUTCROP OF OREBODIES.

By William H. Emmons.

*The outcrops of orebodies are of special interest since it is through them that most deposits are discovered. Now and then a 'blind lode' is uncovered by a chance excavation, or through some fortuitous circumstance the true character of an outcrop may be recognized. Such was the case at Cobalt, where the first discoveries were made while grading for a railroad, but chance discoveries are rare indeed, compared with those which are made by prospectors with whom exploration is a business. The discovery of the outcrop of the ore, and the first recognition of its meaning, are events of prime importance in connection with the economic history of a mining district, and as a rule one may learn a good deal about the outcrop of the ore first discovered by referring to a reliable history of the district. Although there are orebodies which do not outcrop, most of these are discovered after the value of outcropping deposits has been proved in the same district. It is not considered good practice to attempt deep exploration unless there are some exposures in the district at the surface or in the shallow workings which promise reward for deeper and more expensive prospecting.

Outcrops are interesting also because these portions of the deposits have had, as a rule, a more eventful geological history than any other part, and they are situated at the surface of the earth where changes are most rapid. An outcrop may represent a portion of the deposit which has once been primary ore and which has become the zone of sulphide enrichment; at a still later date, the zone of oxidized sulphides; and later still the zone of leached oxides. Last of all, as the surface is worn away, the deposit also is denuded. The component materials are broken up and carried away, either in solution or mechanically. If in solution, they may enrich the deposit lower down, or they may join the general surface circulation and be scattered. If they are removed mechan-

*Published by permission of the Director of the United States Geological Survey, in the *Mining and Scientific Press*, December 4 and 11, 1909.

ically the heavier portions may accumulate as placers, or if the conditions for this are unfavorable they may be lost. Thus the cycle is completed. The study of outcrops is a study of the effects of weathering and erosion of ore deposits. The effects of weathering are shown in the topographic expression of the outcrop, and in the composition of the oxidized zone, in general, and with respect to value.

The topographic expression of lode-deposits depends upon the difference in the rates at which the deposit and the country rock are eroded. If the deposit is more resistant to erosion than the country rock, the latter will be removed more rapidly and the lode may outcrop as a ridge or knob. If the country rock is more resistant than the orebody, then the deposit may occur at the bottom of a slight depression where blocks of hard vein-quartz are mingled with the rock débris. If there is no marked difference between the rate of weathering of the deposit and the rate of weathering of the country rock, the deposits may be found in any topographic position, and for the lode-deposits of the western part of the United States, this is most common. There seldom is here a conspicuous relationship between the outcrop of the deposits and the large features of the topography, although in many California districts, and in some of those of Nevada, as at Goldfield and at Mineral Hill, some of the minor features of the relief may be controlled by the lodes.

It is not unusual to find differences in the character of topographic expression of the deposits of a single district, or even in a single lode. At one place it may outcrop as a ridge, in another along a ravine. The difference must be great before considerable permanent relief is established, for the rock of a ridge is in an exposed position, and is, therefore, the more readily attacked by agents of weathering. The great majority of the orebodies are lode-deposits. They are for the most part rudely tabular, and there is accordingly a tendency for their intersection with the surface to be expressed as a line usually curved, the curvature depending upon the topography and the dip of the lode, or upon an actual bend of the lode along the strike. The relief is variable, and is an expression of the relative rate of erosion of the lode and country rock. Fig. 1 shows a conspicuously outcropping lode.

With respect to the ratio of the rates of erosion of the lode-deposits and the country rock, it is unsafe to make too sweeping generalizations, for the rate of erosion of each depends upon many variables aside from composition; but there are some more or less constant features which should be recognized. For the sake of comparison the deposits may be loosely grouped as follows: (1) Silicious lodes in limestone or other soluble or easily eroded rocks; (2) pyrite-rich lodes in limestone or other soluble rocks; (3) silicious deposits in igneous rocks (granites, porphyries, etc.); (4) quartz-pyrite lodes in granites or in porphyries; (5) silicious deposits in quartzites; (6) pyrite-rich deposits in quartzites.

FIG. 1. OUTCROP OF A LODE IN STEINS PASS DISTRICT, NEW MEXICO. (Photo., Graton, U. S. Geol. Survey.)

1. As a rule the highly silicious ores in limestone and other soluble rocks outcrop conspicuously above the surrounding country. The difference in the rate of erosion of the ore and country rock is probably a maximum for such deposits, consequently these deposits are often the first to be recognized, and many camps in the western part of the United States owe their discovery to this. The Hope mine, at Philipsburg, Montana; the Mineral Hill mine, in Eureka county, Nevada; the original Bullfrog mine at Bullfrog, Nevada; (Fig. 2), the quartz outcrops in serpentine along the Mother Lode of California; some of the lodes of the San Juan in Colorado, and many other deposits, may be cited as examples of boldly outcropping quartz bodies which are bounded on one

or both sides by limestone or by other rocks which are eroded at a relatively rapid rate. Most of these deposits contain a high percentage of quartz, and the ore commonly contains more than 90% silica. If the calcareous wall-rock has undergone much metamorphism it is more resistant to erosion than before, and the outcrops are usually less conspicuous.

Fig. 2. Outcrop of Original Bullfrog Lode.

The small hill in the foreground is composed in part of solid quartz which dips at an angle. The country rock is rhyolite and limestone. (U. S. Geol. Survey. After Ransome, Emmons, and Garrey.)

2. As pyrite increases in such deposits the outcrop is likely to be less conspicuous. The pyrite alters to the hydrous iron oxide, limonite. This alteration is attended by a loss of sulphur and some iron, which substances are removed as iron sulphate; there is also an addition of oxygen and water. As a result there is a loss of volume, as is shown by pseudomorphs of limonite after pyrite, which when broken open are usually found to be cellular. Although limonite is relatively insoluble in the common underground waters—perhaps even less soluble than silica, the oxidation may leave a powdery mass which is easily washed away, and as a result the pyritic cropping is nearly always less resistant than the limestone wall-rock. Accordingly the highly pyritic deposits will outcrop in slight depressions or on hillsides. Lodes of highly pyritic gold ore and pyritic copper seldom stand up conspicuously above the surface of limestone, but are recognized from the color of the surface rather than its relief.

3. Silicious deposits in igneous rocks are eroded by earth-waters

at a rate which on the whole is little less rapid than the erosion of the country rock. As a result such deposits are likely to outcrop above the general surface, but the outcrops are not so conspicuous as those of the silicious deposits in limestone. The difference is not so great as the difference between the erosion of silicious ores in limestone, nor is it so nearly uniform. It depends in a larger measure upon the extent to which the silicious lode has been fractured since it was deposited, and if fracturing has been extensive, such a deposit may be eroded at a more rapid rate than the igneous rock; indeed, a part of such a deposit may form a conspicuous depression, especially where the lode crosses a ridge, although other portions in which the ore is less fractured may outcrop a little above the surface. On the other hand, certain kinds of hydrothermal metamorphism of the igneous rock, and structural features such as jointing, sheeting, and vesicularity, may make it more easily eroded and then the deposit may outcrop as a ridge. An outcrop of a silicious orebody in eruptive rocks is illustrated in Fig. 3.

4. Pyritic lodes in igneous rocks are usually eroded more rapidly than the rock. As pyrite increases in the lodes which cut the porphyries and other igneous rocks, their outcrop becomes less conspicuous, and if much pyrite is present these deposits are likely to lie a few feet below the level of the country. Between the silicious and pyritic lodes is a great class of deposits which carry considerable quartz and also a notable amount of pyrite, and such deposits are likely to be eroded at about the same rate as the country. Outcrops of this character are numerous, and perhaps they exceed all others. The presence of the lode is not indicated by any constant topographic feature. At most places there is not the slightest ridge or the faintest depression, but here and there, perhaps, or at only one place along the lode, the adjacent country rock may have been ground up by movement, which nearly everywhere follows the walls of the veins more or less closely. If the post-mineral fissuring has left the vein for the country rock in only one favorable place, that circumstance may be responsible for a little more rapid erosion at that place, making an exposure of the lode. Many of these lodes are found where they are crossed by small canyons or in cliff exposures due to other causes, or by following float up the hillside and trenching here and there for the lode, or again by investigating small depressions or other areas in which the loose soil and rock are stained by limonite. Butte and Granite, in Montana, afford good examples of lodes in igneous rocks which may at one place outcrop just a

trifle above the general surface, but which at other places on the same lode may be found below a slight depression. In both these districts there has been considerable post-mineral fissuring which in the main follows the lodes. With a few exceptions there are no long continuous outcrops of lodes in either of these camps. Here

Fig. 3. Surface Workings of the Anaconda Vein, Cripple Creek, Colorado.
The lode is a sheeted zone of silicious tellurium ore and the country rock is volcanic breccia.
(U. S. Geol. Survey. After Lindgren and Ransome.)

and there a slight depression may mark the apex of a lode, but at most places there is not enough difference between the rate of erosion of the ore and country rock to find expression in the topography.

5. Silicious deposits in quartzite weather at about the same rate as the quartzite, and the problem of their discovery is similar to that of the lodes just considered.

6. If, however, there is a notable amount of pyrite in the ore it weathers more rapidly than the quartzite, and as a result the apex of the deposit is obscured. Quartzite, on account of its erosion-resisting qualities, is an unfavorable rock for ore outcrops, and this fact, together with its comparative insolubility in most replacing solutions, probably justifies the prejudice against it which exists in the mind of the prospector. While a few important deposits have been found in quartzite, their number is small, indeed, compared to the deposits which have been discovered in limestone and in igneous rocks. Perhaps this difference is emphasized in no small degree by the unfavorable conditions controlling outcrops.

Orebodies which are less resistant to weathering processes than the country rock are, as already stated, difficult to find. A long depression in such a position that it does not seem to be a natural drainage-channel may cover such a deposit and should be trenched for investigation. When deposits of this nature have been found and followed a short distance underground it is good practice to outline with pegs the trace or apex of the orebody on the surface, and to peg out in both directions the position which the orebody would take if its dip and strike remain unchanged. In this way it may be followed through outcrops of country rock and over grassy unexposed portions of the surface, and by trenching it may be found. In a hilly country with veins which are not vertical, it is convenient to use a plane-table and a flat board for sighting. The table is placed on the apex of the lode and leveled. A thin board is trimmed to an angle corresponding to the dip of the vein and a second rectangular board is placed against this on the plane-table so that its upper edge points in the direction of the strike of the lode. It is then oriented exactly with the lode, and by sighting along it pegs may be driven anywhere on the hillside, and should be exactly on the apex of the extension of the lode providing its attitude remains unchanged. If its attitude does change, the change is often shown by outcrops of country rock in the strike of the extension shown by sighting along the board.

Changes in Depth as Indicated by Outcrops.—To some extent the difference in the rate of erosion of the ore and country rock may give a hint as to the relative size of the lode in depth. If the deposit varies greatly in width down the dip, and if it is eroded much less rapidly than the country rock, then in a majority of cases its width will decrease in depth. If, on the other hand, the country rock is eroded less rapidly than the deposit and the lode varies in width down the dip, its width will increase in a majority of cases. If the lode is very resistant and the country rock easily eroded, then the lode outcrops above the surface, and the wider part of the lode will outcrop for a longer period of time than the narrower part, hence, if there be several deposits of this character, most of them will be found at a time when a maximum amount of the hard rock is exposed to erosion. Fig. 4 illustrates this case. The lode is more resistant to erosion than the country rock and outcrops as a ridge. The solid line, which is an erosion-surface showing a maximum amount of the hard rock, may be called a permanent surface, while the dotted line, showing a maximum amount of the soft rock, may be called a temporary surface. If, on the other hand, the deposit be less resistant than the country rock, and if it vary in width down the dip, the narrow portion is likely to remain at the surface longer, as shown by Fig. 5, where the solid line represents the 'permanent' outcrop, and the dotted line the 'temporary' outcrop. Such a deposit is likely to increase in size as it is followed downward. In other words, the erosion is such that a maximum amount of the most resistant material, be it ore or country rock, tends to remain longest at the surface, and as far as possible to monopolize the outcrop. Not all, but the majority of such deposits will increase in size with depth. Examples where large masses of quartz outcropping in limestone are underlain by relatively small bodies of quartz in limestone are common. Among such deposits are the lodes of Mineral Hill, Nevada, the Cadgie Taylor mine, Montana, and many other deposits of silicious ore in soluble rocks. On the other hand, some of the soft lodes of fissured decomposed quartz and clay which outcrop at Bullfrog, Nevada, in relatively resistant rhyolite, have shown a fairly consistent tendency to increase in width down the dip of the deposit from the apex to near the bottom of the oxidized zone.

Composition of Outcrops and Leached Zones.—Since pyrite is an important mineral constituent in nearly all primary gold, silver, and copper ores, the color of the oxidized outcrop is red or brownish yellow, depending upon the amount of limonite present. Brown shades may be shown locally, due to manganese stains, as at Bullfrog and Manhattan, Nevada; or if this oxide is in great quantity the color may be black, as at the outcrops of some deposits at Philipsburg, Montana. The composition of the oxidized zones is discussed authoritatively by R. A. F. Penrose, Jr., in his paper on the 'Surface Alterations of Ore Deposits.'[1] The minerals of the outcrops and

[1] *Jour. Geol.*, II, p. 288.

oxidized zones are the residual primary minerals which remain behind owing to their relative insolubility and to the secondary minerals formed by oxidation and kindred processes. The residual minerals are essentially those which commonly occur in placers, and include gold, platinum, cassiterite, rutile, zircon, and some gems. In addition to these minerals galena and quartz are often found. These substances are much less soluble than pyrite, zincblende, and antimony sulphide, and so may be found as small remnants at or near the surface, mingled with the minerals of the oxide-zone, and at some places they may be found in placers.

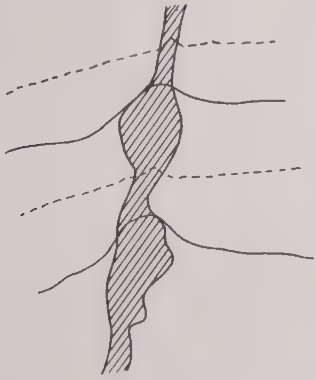


FIG. 4.

Cross-section of a lode which varies in width down the dip and which is more resistant to erosion than the country rock. The solid lines show the 'permanent' surface. The dotted lines show the 'temporary' surface.

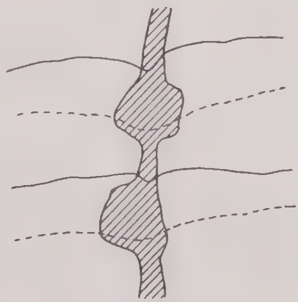


FIG. 5.

Cross-section of a lode which varies in width down the dip and which is less resistant to erosion than the country rock. The solid lines represent the 'permanent', the dotted lines the 'temporary' surface.

Magnetite and specularite resist the agents of weathering longer than pyrite, and in deposits where the three occur together the magnetite and pyrite may appear at the outcrop, together with a considerable quantity of limonite, which is an alteration product from pyrite. The pseudomorphs of limonite after pyrite may be intergrown with the residual magnetite. Galena is dissolved slowly and is often found in an unaltered condition. Enargite seems to be one of the most insoluble minerals, and so in the few deposits where it is a primary mineral it may appear in or just below the outcrop. At places in Tintic, Utah, according to L. C. Graton, pyrite, chalcopyrite, and other sulphides have been dissolved out of the higher zones, and galena and enargite only remain. At other places enargite remains and galena has been dissolved.

Secondary minerals formed in the oxidized zone by oxidation and kindred processes are given below. The amounts of these minerals vary greatly, depending upon the composition of the ore before oxidation, upon the relative solubility of the minerals, and upon the earth-waters causing weathering, the nature of the country rock, and upon other conditions and processes.

Native elements: Amalgam, antimony, arsenic, bismuth, copper, gold, lead, mercury, silver, sulphur, tin.

Oxides: Bauxite, cuprite, hematite, kaolin, limonite, magnetite, melaconite, molybdite, psilomelane, pyrolusite, turgite.

Sulphates: Alum, alunite, caledonite, celestite, chalcanthite, goslarite, leadhillite, gypsum (barite and strontianite in part.)

Carbonates: (Ankerite), aragonite, aurichalcite, azurite, calcite, cerussite, dolomite, hydrozincite, leadhillite, siderite, smithsonite, witherite, magnesite.

Silicates: Calamine, chalcedony, chrysocalla, chert, opal.

Phosphates: Pyromorphite, pseudomalachite.

Chlorides: Cerargyrite, pyromorphite, alacamite, bromyrite, calomel.

Many of these minerals are the result of the oxidation of the primary sulphide ore, but some result from oxidation, reduction, or chloridation of the secondary sulphides. This is true in a large measure of the rich copper and silver minerals.

Extent of the oxidized zone. In countries which have been glaciated in the last glacial period the sulphide ores often outcrop at the surface. In Alaska and in New England, where the ice erosion was vigorous, such outcrops are most common. If any extensive oxidation took place below the ice the oxidized ore was removed by ice-erosion.

For countries which have not been recently glaciated the vertical extent of the oxidized zone depends, in a broad way, upon the depth of the water-table below the surface. Oxidation may take place below the water-table, but this is not often pronounced, and may be regarded as an interesting feature rather than as an economically important one. Often, the bottom of the oxidized zone is above the water-table. This is particularly the case where the lode is little fractured. It is likewise true where the water-table has lately been depressed through change of climate to aridity, as in the Great Basin of the United States, or where stream beds through which the lodes are drained are being rapidly lowered by erosion, as is often the case in mountainous regions. Indeed, it is common to find the sulphide ores marooned high above the water-table, and these may oxidize in place to rich silver and copper minerals. S. F. Emmons[2] has divided the oxidized zone into two sub-zones, the lower zone of rich oxidized ore, and the upper zone of leached oxides. The depth of the latter is controlled to some extent by the position of the water-table, but depends mainly upon processes of leaching which are discussed below. The presence of this zone is quite generally recognized, but data relating to its depth are obviously of considerable importance, especially to the prospector or to the miner who is engaged in opening a property.

Outcrops of gold deposits. Gold deposits undergo important changes at the surface of the earth. The work of C. L. Doelter,

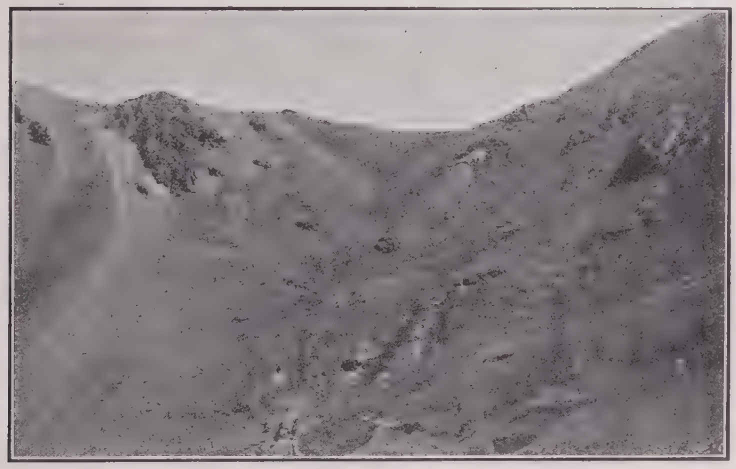


FIG. 6. OUTCROP OF VEINS NEAR LAKE COMO, SILVERTON, COLORADO.

The lodes in the foreground are silicious deposits in altered andesite and latite.

(Photo., Ransome, U. S. Geol. Survey.)

G. F. Becker, H. N. Stokes, V. C. Lenher, and others indicates that gold is dissolved by concentrated solutions of many salts which are found in earth-waters, but in the main at temperatures near or above the boiling point of water. Reactions under such conditions cannot have been important in changing outcrops of gold deposits, for the maximum temperature at which the reactions take place is known to be about room temperatures, and the pressures do not greatly exceed 15 lb. per square inch. Ferric sulphate, which

[2]Trans. Amer. Inst. Min. Eng., XXX, p. 177.

is usually present in mine-waters, does not dissolve an appreciable amount of gold at ordinary temperatures, but if ferric chloride is present also, and especially if manganese oxide is present, gold is dissolved much more readily, as has been shown by a number of investigators, among them J. R. Don, T. A. Rickard, and V. C. Lenher. Native metals, oxides, soluble reducing salts, and some forms of carbonaceous matter, are known to precipitate gold from the above solutions. Indeed, of all the commoner metals, gold salts are the least soluble, consequently gold is difficultly dissolved and easily precipitated, and so gold does not travel far below the outcrop, and consequently the zone of leached oxides vertically is not extensive. There are no examples of gold deposits of proved secondary enrichment which are at all comparable in size and richness to the secondary sulphide deposits of silver and copper. It is not uncommon, however, to find the richest part of a gold deposit just at the surface or more often just a few feet below the surface and extending downward to the bottom of the oxidized zone. The process of oxidation is at first one of enrichment,[3] but if the process goes far enough it may result in depletion of the metal. This depends upon the rate of solution of the mineral components of a gold deposit. Take the commonest type composed of quartz, pyrite, and gold, the precious metal being contained as free gold in both the pyrite and quartz. As this ore weathers, pyrite is broken down first through oxidation. The sulphur and some of the iron are carried away as iron sulphate. The amount so removed is considerable. In the Granite-Bimetallic mine it is 0.6 of a ton every 24 hours. But a large part of the iron remains behind as limonite. Silica is dissolved and carried away, as is also the relatively insoluble limonite. Gold may be dissolved if chlorides and manganese are present and to some extent in their absence. If gold is not dissolved there is enrichment due to the removal of other constituents. If it is dissolved in greater proportion than the base elements, the outcrop is impoverished. The rate of solution of gold, and consequently the depth of the leached zone, and the presence or absence of associated placers, depends upon the size of the gold particles, and probably to a considerable extent upon the presence of manganese oxide in the oxidized ore Waldemar Lindgren, comparing the Mesozoic gold deposits of the Pacific Coast and elsewhere with the gold deposits associated with the Tertiary eruptions,[4] notes that important

[3]T. A. Rickard, Trans. Amer. Inst. Min. Eng., Vol. XXI, p. 198.

[4]Trans. Amer. Inst. Min. Eng., 1902, p. 790.

placers have been derived from the former, and that the Tertiary deposits of the Great Basin and elsewhere have contributed but little placer gold. The gold, being in a more finely divided state in the late Tertiary deposits, is more readily dissolved, or is more likely to be carried away.

In the Philipsburg quadrangle, Montana, I had a good opportunity for examining two types of gold-bearing deposits within a relatively small area. In one of these (Granite-Bimetallic lode) the gold is fine, and considerable manganese carbonate is present in the primary ore. This, oxidizing, gives a notable amount of chocolate-colored manganese oxide, which is present in nearly every outcrop and in the oxidized zone to considerable depths. There are no placers associated with these deposits, and the outcrop carries less gold than the lode at a depth of 50 to 200 ft. below the surface. In the other type of deposit (Cable mine), gold is for the most part less finely divided, and manganese oxide is entirely absent or extremely rare. These deposits yield rich placers, and they have been stoped to the surface. The leached or impoverished zone varies from nothing to 50 ft. and begins rarely more than 30 ft. below the surface. In the Comstock lode, which has yielded many millions in gold, but no relatively important placers, much manganese oxide is found in the upper levels. According to Clarence King,[5] "A zone of manganese oxide occupies the entire length of the lode from the outcrop 200 ft. down." Tonopah, Bullfrog, and many other camps in Nevada, may be cited as examples where there are no rich placers, and where a notable amount of manganese oxide is present in the oxidized ore. In these camps, as a general rule, the outcrop, and a shallow zone below, carry less gold than the deeper oxidized ore. The same statement may apply to the Granite Mountain lode, in Montana, and to the Butte deposits. At first glance the latter seem to be exceptions to the generalization that manganese is unfavorable to the formation of placers and favorable to leaching, for there is considerable manganese in the Butte veins, and yet the camp was first exploited for its placer gold. As is well known, there are three periods of mineralization shown by the Butte deposits, and the deposition of rhodochrosite seems to be limited to the deposits of one or possibly to two of these periods. The small amount of placer gold which has been won at Butte may well have come from the manganese-free deposits. On the other hand, the placer-yielding lodes of the Pacific Coast carry little or no manganese oxide, and

[5]'Fortieth Parallel Exploration,' Vol. 3, p. 75.

this circumstance may be responsible to some extent for the great accumulations of placer gold and the small amount of leaching which the deposits of this class have undergone. In general, coarse gold and freedom from manganese are favorable to the enrichment of placers and are unfavorable to the leaching of the upper part of the oxidized zone. Consequently, shallow exploration, usually not more than 50 ft. in depth, is sufficient to prove the value of a deposit of this character, providing the work is done on an ore-shoot. Finely divided gold, and the presence of manganese oxide, are unfavorable to the formation of placers and are favorable to leaching of the upper part of the oxidized zone, but this does not

FIG. 7. A QUARTZITE LODE IN ALTERED ANDESITE, VALLEY VIEW MINE, TONOPAH, NEVADA.

The outcrop and open-cut show in the foreground.

(Photo., Spurr, U. S. Geol. Survey.)

seem to take place to any great extent much lower than 100 ft. below the outcrop of the deposit, but where there is considerable fissuring, and the ground is open, leaching of gold may extend to greater depths, and in such places it may be necessary to sink deeper to be sure that the leached zone has been passed, but for mines where gold is the only important metal sought, 200 ft. in depth seems a safe figure.

Recent inspection of a large number of stope-sheets of gold mines indicates that even where gold is finely divided, and manganese is present in the veins, the majority of outcropping orebodies are stoped to less than 50 ft. from the surface. Briefly stated, in the average gold deposit, which outcrops at the surface, the workable ore is encountered at the surface or within 25 or 50 ft. of the surface, but in some cases it is found 100 ft. below the surface, and exceptionally, 200 ft. below the surface, depending upon the fineness of the gold particles, the presence of manganese dioxide, and the amount of post-mineral fissuring.

Outcrops of silver deposits. Most silver minerals are readily dissolved by surface-waters, and the leaching may at some places extend to greater depth than the leaching of gold. Silver enters into the composition of a great many minerals, chief of which are the native metal, the halogen compounds, the sulphide, the sulph-arsenic, and sulph-antimony compounds. Silver is also contained in the sulphides of the other metals, especially in galena, pyrite, and zinc-blende. A large proportion of the silver ore is of this character. At 18°C. in pure water silver salts have the following order[6] of increasing solubility: I, Br, Cl, CO_3, C_2O_4, OH, SO_4, ClO_3, NO_3, F. The solubility of the sulphate is 0.55 grain in 100 c.c., or nearly three times the solubility of gypsum, which is commonly regarded as a soluble mineral. The silver sulphate is formed by the oxidation of the sulphide and other silver compounds or by the action of ferric sulphate[7] on silver compounds. This reaction takes place at the lower temperatures, and therefore may be important under the conditions at which silver ores are exposed to agents of weathering. Accordingly in the presence of sulphate-waters silver minerals are readily dissolved and carried away in solution. The sulphates in solution may be reduced by sulphides[8] of Cu, Pb, Fe, and Zn, in which case the silver will form a secondary sulphide which is relatively insoluble and easily precipitated, or if it is not precipitated it may be carried away from the deposit in the general underground circulation.

The chloride of silver is relatively insoluble. At 18° only 0.0016 grain will dissolve in a litre of pure water, which is a small fraction of 1% of the amount of silver sulphate which is so dissolved. On account of its comparative insolubility the chloride, horn silver, will be precipitated from silver sulphate solutions in the presence of chlorides. Being relatively insoluble in earth-waters it is not easily removed, and so at many places it is present in important quantity

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[6]As measured in moles per litre, determined by Kohlrausch by the conductivity method.

[7]H. N. Stokes, *Econ. Geol.* I, p. 649.

[8]S. F. Emmons, Trans. Amer. Inst. Min. Eng., Vol. XXX, p. 177; W. H. Weed, Trans. Amer. Inst. Min. Eng., Vol. XXX, p. 424.

at the very outcrops of silver-rich orebodies. As pointed out by R. A. F. Penrose, Jr.,[9] silver chloride forms extensively in the upper part of silver-rich orebodies in the arid regions of the United States, especially in the Basin province. The earth-waters there carry much chlorine owing to the poor drainage as a result of which salt lakes and marshes have formed at many places. It is well known that salt is vaporized in sea water, just as H_2O is vaporized. It is carried down to the earth in the rains, and there is a continual circulation of NaCl from the ocean to the land and back to the ocean, just as there is a circulation of H_2O. Although the salt circulates in very small quantities, the amount is quite sufficient to form important bodies of silver chloride. The effects of the circulation are shown 100 miles inland from the sea,[10] and so within 100 miles of a body of salt water we may expect to find the chlorine in rain water. Further, there is residual chlorine in some of the sedimentary rocks, and so the conditions for the precipitation of the chloride may hold at places far removed from salt water. The abundance of chloride formed is not in direct proportion to the salt present in earth-waters even when other conditions are constant, for silver chloride dissolves in an excess of the alkali chlorides, and the presence of too much salt will cause the chloride to re-dissolve and be carried away from the outcrop. Perhaps this is the reason that some silver chloride deposits are a little richer a few feet below the surface than at the outcrop. However that may be, there is a strong tendency to concentration at or just below the outcrop of the silver lode, and this is most marked in arid regions, so much so that the word 'chloriding' was very generally used in such regions for pocket-hunting near the surface in the early days of mining in the Great Basin States.

Native silver, like the chloride, is often found at the outcrop of the lodes. In nearly all deposits of the western Cordillera it is clearly the reduction-product of the sulphide, chloride, or other silver salt. J. E. Spurr in a recent article[11] emphasized the abundance of native silver and the absence of ruby silver at Aspen, Colorado, where shale often forms one of the walls of the deposit. At Georgetown and other camps near by, the ruby silver is a common and sometimes abundant secondary mineral, and the native silver relatively rare. The complete reduction of the silver salts to the

[9]'The Superficial Alteration of Ore Deposits,' *Jour. Geol.*, II, p. 288.

[10]T. M. Brown, quoted by F. W. Clark, 'Data of Geo-Chemistry,' p. 47, Bull. 330, U. S. Geol. Survey.

[11]*Econ. Geol.*, Vol. IV, p. 301.

native metal has here been accomplished by the shale which is rich in carbonaceous reducing agents. Native silver may, however, occur in considerable quantities in oxidized ore where no shale is present, as in the Granite-Bimetallic lode in Philipsburg mountain, and in a great many other silver lodes. The commonest type of the rich silver outcrop is composed of spongy iron-stained quartz plastered with horn silver, and carrying thin flakes of native silver.

Fig. 8. Outcrop of Drinkwater Vein, Near Silver Peak, Nevada. (Photo., Spurr, U. S. Geol. Survey.)

Pyromorphite, the lead chlor-phosphate, often carries silver, and in Montana, Colorado, and Nevada this mineral frequently appears in the outcrop. Silver bromides and iodides form to some extent. In pure water at 18°C. these silver salts are less soluble than the silver chloride. But since bromine and iodine are much less abundant than chlorine, the iodide and bromide of silver are not common. I have made a large number of tests of suspected bromides taken from outcrops in Montana and Nevada, and have never had a satisfactory test for bromine in any of them. The law of mass action enters here, and accordingly the halogens other than chlorine play a subordinate rôle in the outcrops of most silver lodes.

There are many shoots of silver ores which are not everywhere workable at the surface, and in some of these the chloride is among the silver minerals. Notwithstanding the relative insolubility of this mineral, and the general presence of chlorine in earth-waters, some of the outcrops of silver lodes are leached to a considerable depth below the outcrop. Characteristically the oxidized zone may extend from the surface to the level of the ground-water, or slightly below this level, depending largely upon the fissuring to which the ore has been subjected. In the Comstock[12] lode this oxidized zone extends in places 500 ft. below the surface, whereas at other places the sulphide continues to the surface. In the Granite and Bimetallic mines, incomplete oxidation has taken place deeper still, and in the Mizpah mine, at Tonopah,[13] some oxidation extends to a depth of 700 ft. In all of these mines the bottom of the oxidized zone is irregular, depending largely upon fracturing, and in all of them leaching seems not to have taken place to any great extent below the middle of the zone of oxides. Inspection of a number of stope-sheets of silver mines shows that most silver lodes are at some place workable at the surface; but that there is also a fairly constant horizon from 75 to 200 ft. below the surface that represents the top of the zone of workable ore. In some mines where there has been considerable fracturing of the ore since it was deposited, there has been some leaching locally as deep as 400 ft. below the surface, but this depth should probably be regarded as near the maximum for silver deposits. Leaching seems to have been important on the average less than 200 ft. below the surface, and unless the ground is open and the circulation very free, the oxidized ore-shoot should be payable at that depth. If an important proportion of the metals is gold, the workable ore should be expected nearer the surface than in ore where the gold is a relatively unimportant constituent.

Galena is, as already stated, less readily decomposed than pyrite, zincblende, and antimony sulphides, and it, therefore, lingers longer in the outcrop. It is dissolved, however, for it does not usually occur in great abundance immediately at the surface, but is often

[12] Clarence King, Geol. Expl. of Fortieth Parallel, Vol. 3, Atlas.
[13] J. E. Spurr, U. S. Geol. Surv., Professional Paper 42.

found a few feet below. In Wisconsin many lead deposits have been discovered by farmers who were plowing fields, and in the Coeur d'Alene, Idaho, at Eureka, Nevada, and at Bingham, Utah, some silver-lead deposits were worked from open-cuts. Compared with the silver ores which are rich in arsenic and antimony minerals, the silver-lead deposits are less readily leached of their metal content, and for that reason the workable ore may be found nearer the surface. With respect to shoots of silver ore which do not outcrop, no generalizations can now be made. The leaching of these presents a wider range of possibilities, and, as a rule, no seemingly rational interpretations may be made.

Outcrops of copper deposits. The important copper deposits of the United States fall into two large groups. First, deposits in regionally metamorphosed rocks which are associated with granite-gneisses, diabase, actinolite, schists, and other basic rocks, or which occur as lenses in quartz-biotite schist, quartz schist, and related rock, and, second, deposits of Mesozoic age or early Tertiary, associated with monzonites, granites, their porphyries, and similar rocks. There are no middle or late Tertiary copper deposits in the United States comparable to the silver deposits of that age, just as there are no silver deposits comparable to the pre-Cambrian and Mesozoic gold and copper deposits.

The first group, which is in the main pre-Cambrian or Cambrian, includes the Lake Superior deposits, and the Appalachian deposits of pyritic copper ore, of which Ducktown is the most important example. Of these, two principal types may be recognized. They are (1) native copper in vesicular basalt or diabase; (2) schistose ores in regionally metamorphosed igneous or sedimentary rocks.

The native copper ores in pre-Cambrian conglomerate, basalt, or diabase, are not greatly leached at the outcrop where the rock is tight. These deposits often are found at the surface, the native copper outcropping with the rock, only slightly tarnished or altered to oxides or carbonates. Where the rock is open, there is some leaching of the outcrop, but most of the deposits of this group may be worked to near the 'grass roots.'

Most of the schistose ores in regionally metamorphosed igneous and sedimentary rocks are in the Appalachian States. They are probably the regionally metamorphosed products of ores of varied character, including the fissure veins, magmatic segregations, and replacement deposits. They are, as a rule, tight and not greatly affected by movement since they were formed, consequently they are not leached to great depth, and the primary sulphide ore usually appears at less than 100 ft. below the surface. In the Northern States where the deposits have been glaciated, the primary sulphides usually outcrop at the surface, and even where there has been some crushing the oxidized zone does not usually extend more than from 5 to 25 ft. below the surface. In the Southern States, where there was no Pleistocene glaciation, this zone extends to greater depths, and at Ducktown it is fairly uniform, and from 30 to 50 ft. deep.

The second important group of copper deposits is mainly, if not altogether, of Mesozoic age, or else the earliest Tertiary. This group includes ten of the thirteen leading copper camps of the United States. In all these the igneous rock associated with the ore deposits is diorite or the porphyritic equivalent, or a rock which is more acid. In at least eight of these camps, and probably in all of them, there has been contact-metamorphism, and the development of garnet zones in connection with the intrusion, but in few, if any, is the ore of the garnet-gangue of the first importance. Several types of these deposits may occur in one mining district. The most important classes are: (1) Garnet zones with sulphides intergrown with contact metamorphic silicates; (2) replacements of limestone; (3) fissures in granitic rocks; (4) disseminated chalcocite ores in monzonite porphyry; (5) chalcocite ores disseminated, and in sheeted zones in quartz-muscovite-biotite schist.

The garnet zones outcrop rather boldly as a rule. They alter to limonite, turgite, hematite, kaolin, and other minerals, forming a gossan not unlike a gossan of pyrite in some respects, but weathering is not so rapid. In these zones are often seen bunches of carbonate, oxide, or even sulphide copper ore, directly at the surface, though at some places there is leaching to a depth of 25 or even 50 ft. Not often is there leaching to greater depth. The bunches of rich oxidized ore which at some places are found in the outcrops of the garnet zones probably result from the oxidation of secondary chalcocite ore. Nearly everywhere the garnet zones are worked by open-cuts, a fact which illustrates the superficial character of their leaching.

Examples of garnet zones worked by open-cuts are several of the mines of the Clifton-Morenci group, described by Lindgren in his monograph on the district. Some copper deposits at Bullion, Nevada, also, are stoped at the very surface. The Holland and other mines in the Patagonia district, Arizona, according to F. C.

Schrader, belong also to this class, with which may be included the majority of garnet zones.

Replacements of limestone are so irregular in shape that no comprehensive statement can be made with respect to the depth of their oxidation. Many of them do not outcrop at all. The Copper Queen at Bisbee, which is the greatest mine of this group, outcropped only at one point and then was stoped at the surface. On the other hand, the tops of some other deposits at Bisbee and of other portions of the Copper Queen deposits are too low in grade to work, while the lower portions are bonanza chalcocite ore.

In regions of copper-rich magmas, and especially in zones of actively descending solutions, it would be poor prospecting to

FIG. 9. OUTCROP OF LARGE LODE, FOUR MILES NORTHWEST OF GLOBE, ARIZONA. (Photo., Ransome, U. S. Geol. Survey.)

abandon a large limonite body in limestone at any depth short of several hundred feet, and not then unless the associated sulphides were known to be barren.

Fissure veins in deep-seated igneous rocks include the Butte and the Corbin deposits in Montana, and some scattered mines in other districts. If these veins are strongly fissured since the first filling (and the best of them are), then the copper is carried down 200 or even 400 ft. below the surface. This depth is greater also in areas of abundant ground-water, such as Butte, where of all copper lode camps of the United States the leached zone is greatest. The veins usually outcrop as iron-stained quartz, yellowish brown or red, or, when manganese is present, they are chocolate brown to black. Some are stained with copper carbonate, but they carry little copper at the surface, not much silver, and but a small amount of gold.

The disseminated copper ores in porphyry are perhaps the most important group of copper deposits. They are nearly everywhere of low grade, running from 1½ to 3% copper, but they are so large that they can be mined cheaply, and the mineral composition of the ores is such that they may be concentrated cheaply and with a fair saving. They are found at Bingham, Utah; Clifton, Arizona; and Ely, Nevada, and have been described by Lindgren, Boutwell, Lawson, Tolman, and others. At all of these camps they are inclosed in deep-seated intruding porphyries, the composition of which has a narrow range from a rather acid diorite to a rather calcic granite. At each of these camps the intruding porphyry broke through limestone, and in every case it had the power of inducing contact metamorphism. In all of these camps garnet zones with copper-bearing sulphides were developed in the limestone, and at every camp these have been rich enough to work, but, with the exception of the deposits in the Clifton-Morenci district, the value of the garnet zones is small compared with the deposits in the porphyry itself.

The porphyries which are responsible for these deposits were probably intruded in the same general period of vulcanism. At Clifton, Lindgren found that the intrusives cut the Pinkard formation, which is of Cretaceous age, and he regards the age of the intrusive as late as Mesozoic or very early Tertiary. At the other camps Mesozoic or very early Tertiary sedimentary rocks have not been found in contact with the porphyry, but from broad considerations it is highly probable that the ore-bearing magmas were intruded into the sedimentary rocks in the late Mesozoic, at the very beginning, during, or at the close of the Cretaceous. The deposits themselves show many points of similarity. All of them are formed in zones of fracturing, sheeting, or fissuring, but wide fissures are rarely developed. The country rock is always highly sericitized, but rarely or never contains carbonates. At all of the camps except Bingham the sericitization of the porphyry is so intense that great areas have been converted into a white monotonous rock that in hand specimens gives but little evidence of its true character. It is a difficult task to work out the genesis of these deposits, and it is only on their outer edges where the action has been less intense that their history is shown. Probably a small proportion of the original sulphides consolidated with the rock minerals from the molten magma, but most of the primary ore was formed just after the solidification and the shattering of the country rock, and the solutions were contributed by the still liquid portion of the eruptive below. This is shown by the character of the hydrothermal metamorphism. The ore was deposited in the fractured, shattered, and sheeted zones, and to some extent through replacement, the metals being deposited as sulphides along with the potash which was deposited as sericite. Workings in the ore-bearing monzonite at Bingham, Utah, are shown in Fig. 10.

Fig. 10. Outcrop of and Workings in Copper Ore Disseminated in Porphyry, Bingham, Utah.

(Photo., Boutwell, U. S. Geol. Survey.)

At favorable places these orebodies have been fractured, sheeted, or fissured, and where this has taken place, descending waters dissolving the upper portions of the orebody have deposited chalcocite ores lower down. Some of this chalcocite is massive, but a large part is merely in films on the primary low-grade pyrite and chalcopyrite. The depth to which such chalcocite enrichment descends is seldom more than 600 ft. below the surface, and it often ceases before that depth is attained, but in exceptionally open rocks it may be deeper. The depth to the pay ore, which consists either of the chalcocite or of oxidized chalcocite (carbonates, oxides, and native metal) varies, but usually within rather narrow limits for a given district. At Bingham there is from 50 to 100 ft. of low-grade unworkable rock above the better ore. At Clifton this zone is, according to Lindgren, from 100 to 225 ft. deep. At Ely, according to A. C. Lawson, it reaches a maximum of 500 ft. The last figure is exceptional, however, and probably may be explained by unusual conditions.

The outcrop of these deposits is always strongly leached, and the sericitized feldspar is usually highly kaolinized by surface waters. In color some of the outcrops are almost white, but nearly everywhere they are stained with iron, and then their color varies from a lemon yellow to reddish brown, or, in the more arid countries, to brownish black. Some stains of copper carbonate and copper oxides may be found at the surface, but at many places these are not present even over good deposits of chalcocite ore. The outcropping country rock is usually so highly altered that its constituent primary minerals are beyond recognition in hand specimens. As a rule, the dark minerals are removed entirely, but some biotite may remain where hydrothermal action has been less intense, and to some extent it may be dissolved by hot waters.

Briefly stated, then, it is warrantable to look for these deposits in deep-seated porphyries of Mesozoic age, in the acid diorites or still more acid rocks, and these are extensively developed in the central Cordilleran province, in Sonora, Arizona, Nevada, Utah, and in Idaho and Montana. They are to be sought in the silicious and especially in the potash-rich portions of the eruptives, or in the highly sericitized portion. They are in zones which suffered fracturing shortly after solidification, a large number of small fractures being the more favorable condition for extensive deposition. They are richest where shearing, fracturing, or shattering have taken place since mineralization, permitting a downward movement of water and the deposition of chalcocite. The outcrop is marked by iron-stained sericitized rock, seldom with conspicuous phenocrysts, varying in color from lemon yellow to a dark brown, and rarely showing much copper at the surface. They are of workable grade at depths varying from 15 to 250 ft., and the workable ore may extend downward to 500 or 700 ft. below the surface. They are in areas of copper-rich magmas, in areas of contact metamorphic copper ore, of copper-bearing fissure-veins, or replacement deposits in limestone. Although the most important, they are seldom the only type of deposit represented in the district.

The chalcocite ores disseminated and in sheeted zones in chlorite, biotite, muscovite schists are the last great group to be developed.

All of the important deposits known of this class are found in Arizona and in the Pinal pre-Cambrian schist. They include the Miami deposits at Globe and the recently developed deposits at Ray, Arizona, the Ray Consolidated, Gila, and Ray Central. These schists, which are metamorphosed quartzite sediments according to F. L. Ransome,[14] are abundantly exposed in the Pinal mountains, where they are cut by many intrusives of granite, diorite, and other eruptive rocks. At Globe the intrusion is so intimate that it is impractical to separate the schists from the eruptive rocks on a map of usual scale. According to Ransome, "the brecciation of the schists probably dates back to an early period. At that time the schist laminae were crumpled and broken, presumably under a slight superincumbent load, and the open or lenticular spaces were filled with quartz. The result was a fragile rock, full of small surfaces of weakness, that was thoroughly shattered by later movements." Some veins and zones of fault-breccia cut across the planes of schistosity, and the ore surrounds the breccia fragments, indicating that the mineralization is later than the regional metamorphism. The age of these deposits is probably Mesozoic. They may be contemporaneous with the disseminated ores in porphyries with which they seem to have many points in common. The Schultze granite, which may be responsible for the mineralization, is, according to W. H. Weed, J. E. Spurr, and C. F. Tolman,[15] post-Paleozoic (Tertiary?) in age, and intrusive in the Pinal. The schist is impregnated with chalcopyrite, and contains numerous small veinlets of ore. The chalcopyrite is enriched by chalcocite. There is some leaching at the surface, but exact figures giving the depth of the leached zone are not now available. At Globe the oxidation in the schists is, according to Ransome, much more shallow than in the deposits in limestone, in quartzite, and in other rocks.

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[14]U. S. Geol. Surv., Prof. Paper 12, p. 23.
[15]*Mining and Scientific Press*, November 13, 1909.

SOME CAUSES OF ORE-SHOOTS.

By R. A. F. Penrose, Jr.

GENERAL STATEMENT.

The subject of ore-shoots is so closely connected with that of the origin of ore deposits, that the one cannot be intelligently discussed without more or less reference to the other; but the intention in the present article is to confine the discussion as much as possible to the causes that lead to the concentration of certain valuable materials in rich spots of ore deposits, and not to discuss the original sources of the materials of the ore. Moreover, the following remarks relate largely to ore-shoots in fissures and other more or less deep-seated positions.

In most ore deposits, the ore and the gangue vary in degree of admixture from places where the deposit is largely ore with a little gangue to places where it is largely gangue with a little ore. It is rare that ore of even approximately uniform character occurs throughout a deposit, and the richer material is generally in bodies of varying size, continuity, and shape. When small, these bodies are known as 'nests,' 'bunches,' or 'pockets,' but the larger or richer ones are called 'ore-shoots,' sometimes also 'ore courses,' or 'pay-streaks.' When conditions have been unusually favorable, there are those large and immensely valuable ore-shoots known to the miner as 'bonanzas,' which have produced the wealth of many of the world's famous mines.

In its most restricted sense, the term ore-shoot applies to a part of a deposit richer in certain metalliferous[1] contents than the adjoining parts, the latter being composed of gangue with perhaps more or less disseminated ore. The term, however, is equally applicable to the not unusual occurrence of an isolated body of ore, more or less steeply inclined in a fissure or other position, surrounded

[1]The term shoot is generally applied to metalliferous deposits, but there is no reason why it should not also be applied to non-metallic deposits.

simply by country rock, with no other gangue materials adjacent. Such bodies are often known as 'chimneys,' 'pipes,' or 'necks.' Among miners, the term ore-shoot is also often applied to places where there is widening of the deposit and the ore is more abundant than elsewhere, though not necessarily of higher grade.

The typical ore-shoot is of a more or less columnar shape, dipping vertically or at a steep angle; but most shoots are less regular in form and some are strikingly irregular, protruding and receding on all sides, thinning down in some places to a narrow neck, in others widening into great dimensions and throwing out long arms from the main body. Some ore-shoots, instead of dipping steeply, lie almost horizontally or meander up and down. These forms are especially characteristic of those shoots resulting from superficial alteration, as described later. Some ore-shoots which originally dipped steeply, have been tilted by the folding of the enclosing rocks, and now occupy various positions of incline. Some shoots form lenticular masses, following a fissure for many feet along its course, and finally thinning out at either end into leaner ore or gangue. In fact, sometimes a whole vein is composed of rich ore, and in such a case it is, in a sense, as much an ore-shoot as the forms already described; but the term is usually applied to a more or less circumscribed body of ore, and it is this conception of its circumscribed character, in addition to the greater value of its contents as compared with the enclosing materials, that distinguishes an ore-shoot from a whole vein of rich ore.

Ore-shoots may crop out at the surface or may be found at a greater or less distance below. In depth, they may continue for great distances, or they may terminate at less depth, and may or may not be succeeded by other shoots below. Where several parallel veins intersect a certain stratum in a formation, which is favorable to ore deposition, such as a limestone or other material to be discussed later, an accumulation of ore in a shoot may occur at the point where each vein intersects this special stratum. Thus the shoots in the different veins will occur along the line of the strike of that stratum. In the same way, if several parallel veins cross a certain fissure which promotes ore deposition, as explained farther on, the shoots in the different veins will occur along the line of that fissure. This form of symmetry in the occurrence of shoots is known among miners as 'ore against ore.'

The occurrence of ore-shoots is due to the varying chemical and physical conditions in different places at the time of ore deposition.

C. R. Van Hise[2] classifies them in three groups, those "largely explained (A) by structural features, (B) by the influence of the wall rocks, and (C) by a secondary concentration by descending waters." J. D. Irving[3] classifies ore-shoots as "shoots of variation" and "shoots of occurrence," the former being shoots that vary from the enclosing material only in relative richness in ore, and the latter class being shoots occurring in isolated positions with no other ore of any kind about them. H. V. Winchell[4] classifies ore-shoots as "paragenetic shoots," or shoots developed mostly at the time of the original formation of the ore deposit enclosing them, and "postgenetic shoots," or shoots developed mostly after the original formation of the enclosing ore deposit.

The great difficulty in classifying ore-shoots is that many totally different causes have often combined to produce any one shoot, and the evidence of some of these causes may have been much obscured or even obliterated since that time, so that the determination of just what cause has been uppermost in influence is often impossible. Thus a given shoot may clearly owe its presence, in part at least, to the replaceable character of the wall rock, but if the structural features in the same spot were also favorable to ore deposition, it might be difficult to decide which influence had been the more important. If, in addition to this, the shoot had been clearly enriched by later alteration from above, the complication would be still further enhanced. In the present paper, instead of classifying ore-shoots, the various influences tending to produce them will be grouped under separate headings.

A most important point, however, must be made clear before going on with this discussion, and this is that the influences to be described as sometimes causing ore-shoots, do not always operate in this way. As a matter of fact, most of these influences seem to be practically without effect in far more cases than they have effect, and in some cases they have actually been injurious to the quantity or quality, or both, of the ore. In the cases where they have been favorable to the unusual concentration of ore, however, their effect has often been so very marked that it cannot be doubted.

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[2]Van Hise, C. R. 'Some Principles Controlling the Deposition of Ores,' Trans. Amer. Inst. Min. Eng., Vol. XXX, pp. 27-177.

[3]Irving, J. D. 'The Localization of Values in Ore Bodies and the Occurrence of Shoots in Metalliferous Deposits,' *Economic Geology,* Vol. III, 1908, pp. 143-154.

[4]Winchell, H. V. 'The Localization of Values in Ore Bodies and the Occurrence of Shoots in Metalliferous Deposits,' *Economic Geology,* Vol. III, 1908, pp. 425-428.

INFLUENCE OF MAGMATIC SEGREGATION.[5]

Many bodies of ore occurring in more or less irregular masses in rocks of igneous origin, are supposed by some geologists to have been formed by segregation during the cooling of the magma in which they are found. Other geologists believe that a tendency to such segregation may have occurred during the cooling, but that the orebodies as now found are not altogether due to magmatic segregation, and have been at least assisted in their formation by the later action of vapors and hot waters. The theory of the magmatic origin of certain classes of ore deposits has been gaining much strength in recent years, and in many cases is now very generally admitted. J. H. L. Vogt[6] of Kristiania, Norway, has for years advocated the magmatic origin of various basic segregations, including many deposits of titaniferous magnetite and other ores, in Norway, Sweden, and elsewhere. Among other deposits now generally supposed to have had a similar origin, may be mentioned the titaniferous iron ores of Cumberland in Rhode Island, those in the gabbro of the Adirondacks and of Minnesota, the native iron in the basalt of Greenland, perhaps some of the copper and nickel deposits of Sudbury in Canada and the nickel deposits of Lancaster Gap in Pennsylvania, as well as many other similar occurrences. Deposits of this kind are very different from deposits of more clearly aqueous origin. The ore is generally in more or less irregular pockets, bunches, or larger bodies enclosed on all sides by country rock, not dependent on the presence of a fissure, a contact, an easily replaceable rock, or any of the other usual positions favorable for ore deposition. In such respects they represent a distinct class of ore-shoots. Some geologists even believe that certain gold-bearing quartz deposits occurring in fissures were formed from the siliceous residue of magmas out of which most of the basic materials had previously crystallized.[7]

INFLUENCE OF LOCAL EMANATIONS OF ORE-BEARING SOLUTIONS.

One of the most common modes of occurrence of ore is in fissures, yet the existence of a fissure by no means indicates the presence

[5]The class of shoots represented by magmatic segregation is small compared with the deposits formed by the various processes of aqueous concentration to be described later, but they are mentioned first because, in some cases, they may have been one of the sources of supply of metalliferous materials in later aqueous concentrations.

[6]Vogt, J. H. L. *Zeit. für prak. Geologie,* numerous papers from 1893 to present time.

[7]Spurr, J. E. 'Ore Deposits of the Silver Peak Quadrangle, Nevada,' U. S. Geol. Surv., Prof. Paper, No. 55. Also, 'A Theory of Ore Deposition, *Mining and Scientific Press,* February 22, 1908; *Economic Geology,* Vol. II, pp. 781-795.

of ore. Most all regions, especially those that have been subjected to orogenic movements, are more or less fissured, and sometimes intensely so; but the fissures that have become the receptacle for any important quantities of ore are the rare exceptions and not the rule. The other fissures may be filled with calcite, quartz, silicates, fluorite, barite, and other common gangue minerals, or they may be empty or partly filled with clay selvage and other products derived from the rubbing and the decay of their walls, or they may be lined along the walls with films of siliceous, calcareous, ferruginous, or other incrustations.

When the barren fissures are younger than the ore-bearing fissures, the absence of ore may be because they were not formed until ore deposition had ceased; but in many cases the barren fissures are as old or older than the ore-bearing fissures, and moreover, fissures frequently carry ore in some parts and are barren in other parts. It seems probable that the presence or absence of ore is often determined by the presence or absence of conditions suitable for its precipitation from ore-bearing solutions, but undoubtedly it is sometimes due to these solutions following only certain channels and not others. They probably often rose as fumaroles or thermal springs, spreading along some fissures and not others, and even in the same fissures often rising along narrow chimney-shaped channels, while elsewhere other waters circulated.

In many regions of both cold and thermal springs at the present time, a characteristic feature is the occurrence, in close proximity to each other, of waters heavily charged with one kind of mineral matter and waters heavily charged with another kind, as well as waters carrying very little mineral matter of any kind. Such a condition is especially characteristic of regions of subsiding igneous activity, and in it may be seen a reason why the vents of some extinct springs should be filled with mineral matter of varying kinds and others should carry little or none. Where the mineral matter in the spring was ore-making material, an ore-shoot might be formed; where it was gangue-making material, a deposit of gangue minerals might result, and between these extremes all degrees of admixture might occur. These various conditions offer a possible reason for the occurrence of ore in shoots along certain narrow limits, such as are represented by the channels of thermal springs.

A typical case of a shoot filling a purely local channel is seen in the long columnar orebody at the Anna Lee mine in Cripple

Creek, which varied from 12 to 15 ft. in diameter and was followed down almost vertically for some hundreds of feet (see Fig. 1). At Kalgoorlie, in Western Australia, several mines, including the Brownhill, Oroya Brownhill, Oroya North Block, and Iron Duke, are located on a large chimney of gold ore which may have been formed in a somewhat similar manner. This shoot, when examined in 1904, was from 30 to 50 ft. in width and had been followed on the in-

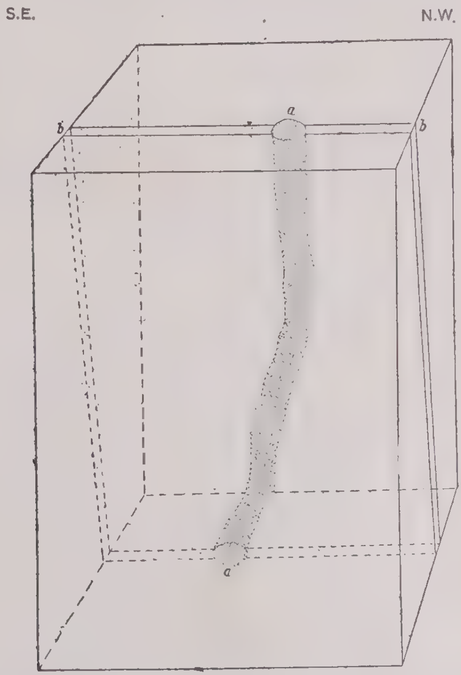

FIG. 1. Section showing ore-shoots at Anna Lee mine, Cripple Creek, Colorado, after R. A. F. Penrose, Jr., 16th Ann. Rept. U. S. Geol. Survey, 1894-5, Pt. II.
a = ore-shoot; b = dike, intersecting volcanic breccia.
Scale, 1 inch = 50 feet.

cline for some 3000 ft., corresponding to a vertical distance of about 1000 ft. This deposit differs from the other gold deposits in the Kalgoorlie district, most of which partake more of the nature of veins in fissures. Again, the Silver King mine in southern Arizona is on a chimney-shaped body of quartz with seams of ore radiating off from it into the country rock.

In some places, small volcanic necks or vents have been filled with igneous materials which have later been impregnated with

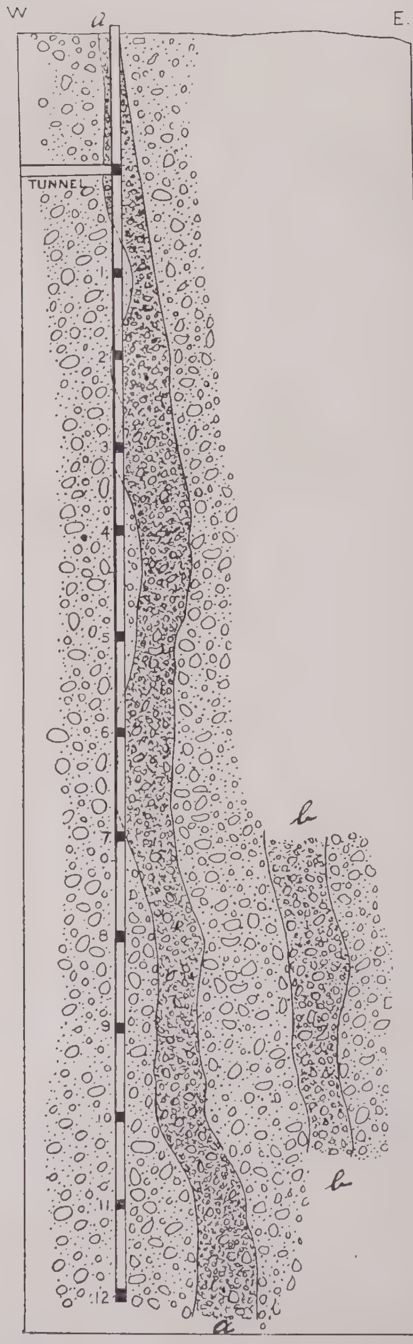

FIG. 2. Section showing ore-shoot at the Bassick mine, Colorado, after S. F. Emmons, 17th Ann. Rept. U. S. Geol. Survey.

a, *a* = ore-shoot intersecting igneous materials; *b*, *b* = subordinate ore-shoot.

ore, forming chimney-shaped ore-shoots. A notable case of this is the old Bassick mine[8] (see Fig. 2) near Rosita, Colorado, which is a volcanic vent filled with fragments of andesite, granite, gneiss, etc., all more or less cemented and encrusted with sulphides. The ore was probably deposited from hot solutions which followed the subsidence of the igneous activity that produced the vent. The Etta tin mine in the Black Hills of South Dakota belongs to a somewhat similar class. It is an intrusive granitic neck which has been later impregnated with cassiterite and other minerals, probably by fumarole action. The diamonds of South Africa occur in somewhat similarly shaped necks, locally called 'pipes', filled with a brecciated mass of igneous material.[9] The Cripple Creek district of Colorado is on a volcanic vent filled with breccia, which in turn is honeycombed with gold-bearing veins; but in this case the vent is so large that the chimney character is not so noticeable as in narrower necks.

INFLUENCE OF GASEOUS EMANATIONS.

The presence of large quantities of gases in coal mines is a generally recognized matter, but the occurrence of gases in metalliferous mines has been much less studied, probably because the gases are in smaller quantities and are less apt to be dangerous; yet in some metalliferous mines they often cause much inconvenience and sometimes danger. They are found issuing from different vents in underground workings, often with considerable force, and consist most commonly of carbonic acid and hydrogen sulphide, but not infrequently of sulphur dioxide, methane (marsh gas), nitrogen, and sometimes other gases. Where these gaseous emanations occur in mines in igneous rocks, they are probably often the remnant of the fumarole or hot-spring action that produced the ore deposit, just as the fumaroles were the remnant of the subsiding igneous activity that produced the rocks of the region. Gases are, therefore, less apt to occur in ore deposits where long intervals have elapsed since their formation than in deposits of younger age. In the older deposits, carbonic acid gas is the most common one found, while in younger deposits various other gases may occur. Gases may also occur in some ore deposits from chemical decomposition of certain minerals, unassisted by any igneous influences. Cer-

[8]Emmons, S. F. 'The Mines of Custer County, Colorado,' 17th Ann. Rept. U. S. Geol. Surv., Pt. 2, pp. 405-472. Also Whitman Cross, 'Geology of Silver Cliff and the Rosita Hills,' 17th Ann. Rept. U. S. Geol. Surv., Pt. 2, pp. 263-403.

[9]Penrose, R. A. F., Jr. 'The Premier Diamond Mine, Transvaal, South Africa,' *Economic Geology,* Vol. II, pp. 275-284.

tain gases may have a precipitating effect on an ore-bearing solution, and where a jet of such gas occurs in the path of a solution, a shoot may be formed, while beyond the limit of the effect of the gas, deposition might cease. Gaseous emanations, when evolved with sufficient strength, may also have considerable influence during the formation of an ore deposit in forcing the ore-bearing solutions along certain courses and not along others, so that the solutions pass upward within only certain narrow limits. By such action they may often have much to do with the position of fumaroles and springs, and hence with the formation of shoots.

Emanations of carbonic acid gas are notably abundant in some of the mines of Cripple Creek in Colorado, of the Thames or Hauraki district of the north island of New Zealand, and many other regions. In the mines of Sulphur Bank in California, in addition to carbonic acid gas, there are hydrogen sulphide, marsh gas, nitrogen, etc., while at Steamboat Springs in Nevada the gases are mostly carbonic acid and hydrogen sulphide.

INFLUENCE OF THE STRUCTURE OF FISSURES.

As explained on pages 337-338, a fissure may differ much in character as it passes from one rock to another, yet even in the same rock its character may vary from spot to spot, both on account of the nature of the movement that produced it and on account of the structural condition of the rock. A fissure passing through a horizontal or regularly dipping rock may have a very different, and generally much more uniform, character than in the same rock much disturbed and folded. A fissure, therefore, whether intersecting different rocks or the same rock, may in one place be a clean-cut break, in another a zone of brecciation, or a series of parallel fissures, or a series of more or less shattered areas connected by comparatively regular breaks, or may assume various other more or less complicated forms. When there has been a fault movement of greater or less extent along a fissure, different parts of the rock may be brought into juxtaposition, leaving cavities separated by places where the walls are close together. In these various ways numerous cavities may be formed, which may influence the position of ore-shoots, not only because they offer the physical space for deposition, but because they afford a better chance for admixture with other solutions which may cause precipitation,[10]

[10]On the other hand, open spaces may be unfavorable places for deposition when they happen to be the channels for waters which have no precipitating action on the ore-bearing solution, and which simply dilute the latter and thus tend to impede or prevent deposition.

and also because they produce a slackening of speed in the ore-bearing solutions that enter them, and may thus cause a deposition of ore which might not occur where the solutions were rapidly moving. In brecciated areas, ore-shoots are apt to occur not only because of the open spaces, but also because there is better opportunity for replacement than in the solid sides of the fissure.

Obstructions, as well as openings, in a fissure may in some cases have an influence on the position of ore-shoots. Obstructions may occur where the walls are locally pressed tightly together, or where the fissure makes a curve or is faulted, or where the decay and rubbing of the walls produce clay selvage, or gouge, which collects and forms obstacles, leaving other parts of the fissure open. Obstructions may also be formed in a fissure in cases where the gangue comes from a different source than the ore, perhaps from the adjacent rocks, and partly fills the fissure before ore is deposited in the remaining space. Obstructions may also occur where the fissure passes from a rock in which it has caused a pronounced break, to a more plastic rock in which it has had very little effect, or even has disappeared, as described on page 338. Any of these obstructions may influence the formation of ore-shoots by locally checking the speed of the ore-bearing solutions that come in contact with them, thus encouraging deposition, or by forcing them into other parts of the fissure not obstructed and thus confining deposition to circumscribed positions, or by forcing them into the wall rock, forming local accumulations of ore either by replacement or by filling interstices and cracks.

A notable case of the different aspects of a fissure in different parts is seen in the great faults on which the Ontario silver mine and other mines at Park City, Utah, are located. The principal fissure in the Ontario mine intersects chiefly limestone and quartzite, with some shale, in the vicinity of an igneous contact. The fissure is sometimes a clean-cut break, sometimes it forks and comes together farther on, enclosing great 'horses' of rock, and sometimes it is represented by a zone of intense brecciation. In some places the walls come close together and but little ore intervenes, in others they widen out and larger bodies of ore occur; while characteristic features are zones of brecciation varying from a few feet to many feet in width, and impregnated with ore. In some places the ore cements this zone into a solid mass, in others it occurs in thin seams meandering through it and separated by areas of loose breccia, forming an open porous vein filling. The fragments of the breccia are mostly limestone and quartzite, and both materials have been more or less replaced by ore, as have also the walls of the fissure and the 'horses' of rock. In places the ore runs out from the main vein for some distance along lines of bedding in the country rock, forming collateral shoots, and gradually tapering out (see page 336).

The Comstock lode at Virginia City in Nevada is another case where the varying character of a great fault fissure affects the quantity of ore from place to place; and in fact many of the important mines of the world illustrate similar phenomena. On the other hand, the Butte copper mines and some of the silver-lead mines of the Coeur d'Alene district of Idaho represent conditions in fissures in which there has been but little displacement, and where the ore-shoots are mostly replacements of wall rock.

In some places the folds in rocks offer structural conditions that influence the position of ore-shoots, even where there is no well defined fissure. Thus at Bendigo, in Australia, the gold ore has accumulated in the crests of anticlinal folds, in sandstone strata immediately underlying slate, in bodies known to the miners as 'saddle reefs'.[11] The sandstone, perhaps more or less shattered by the folding, has offered a pervious channel, and the overlying less pervious slate has confined the ascending solutions to it. Under favorable conditions, ore may also accumulate in a similar manner in synclinal troughs. The latter, however, are better adapted for the accumulation of ore from descending solutions, and some of the iron deposits of the Lake Superior region are accumulations in such positions, due to downward moving solutions meeting an impervious base,[12] instead of upward moving solutions meeting an impervious roof, as at Bendigo.

INFLUENCE OF INTERSECTING FISSURES.

There is a popular impression among miners that ore-shoots are especially likely to occur where one vein intersects another, and sometimes this is true; but as with most conditions under which ore-shoots may be formed, the actual occurrence of the shoot is the exception and not the rule. Nevertheless, important ore-shoots sometimes do occur at vein intersections; and, moreover, they also sometimes occur where a vein of ore is cut by a vein of gangue material or by a barren fissure containing no mineral matter other

[11] Rickard, T. A. Pp. 172 to 189 (this book).

[12] Van Hise, C. R. 'The Iron Ore Deposits of the Lake Superior Region,' 21st Ann. Rept. U. S. Geol. Surv., Pt. 3, pp. 305-434. Leith, C. K., pp. 53-76 (this book).

than rock débris. It is noticeable that this enrichment is not confined to places where strong well defined fissures cut the ore-bearing fissures, but that it occurs also where smaller cracks or even joint-planes intersect them. The occurrence of a shoot at the intersection of two veins containing the same kind of ore, may be due to the fact that the rock was more shattered than usual at such positions[13] and permitted a more ready and copious supply of ore-bearing solutions

FIG. 3. Section showing the occurrence of ore-shoot at the intersection of veins at the Moanataeri mine, New Zealand, after T. A. Rickard, Trans. Amer. Inst. Min. Eng., Vol. XXXI, p. 271.
A B = vein; *C. D.* = vein.

than elsewhere, or it may be due to the fact that where solutions in two fissures meet, their speed is slackened and a deposition of ore may occur which would not have taken place from more rapidly moving solutions. In the same way, if one fissure is faulted by the other, deposition of ore may occur as the result of the checking of the progress of the solutions at the fault.

[13]This action is most apt to occur where the fissures meet at low angles, thus forming wedge-shaped bodies of rock which are more easily shattered on their edges than the blocks formed by fissures coming together at high angles

When a shoot occurs at the intersection of a fissure that carries ore and one that is barren or carries only gangue minerals, the latter may have acted as a channel for certain solutions different from the solutions in the main fissure, and of such a character as to cause a precipitation of mineral matter from the solutions in the main fissure, which might not otherwise have occurred. In other cases, the influence of the cross-fissure may have been purely mechanical, deflecting the metalliferous solutions and confining or guiding them to advantageous positions of deposition. Sometimes cross-fissures, instead of supplying solutions, may act as channels

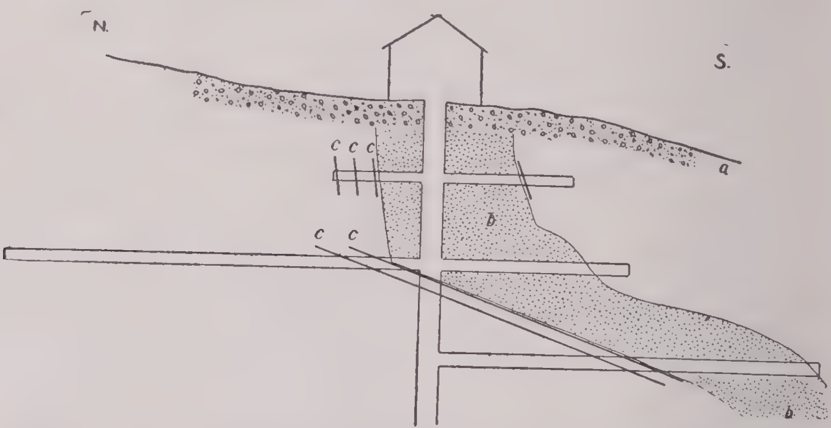

FIG. 4. Longitudinal section showing ore-shoot at the intersection of fissures in the C. O. D. mine, Cripple Creek, Colorado, after R. A. F. Penrose, Jr., 16th Ann. Rept. U. S. Geol. Survey, Pt. II.
a = surface débris; *b* = ore-shoot; *c*, *c*, *c* = cross-fissures.
Scale, 1 inch = 50 feet.

through which the ore-bearing solutions in the main channels are carried off into the country rock, depositing 'stringers' of ore, which gradually taper out at a short distance. Where a number of cross-fissures intersect the ore-bearing fissure and also each other, they form blocks of country rock in the walls, which may be replaced by ore in much the same way as the 'horses' of rock described on page 334. An effect similar to that caused by a cross-fissure is sometimes produced where the main ore-bearing fissure crosses an especially well marked line of stratification in sedimentary rocks, this line having often the same influence as a cross-fissure.

The favorable influence of intersecting veins and fissures on ore-shoots is seen in many well known mining districts, such as Aspen and Cripple Creek in Colorado, the gold regions of California, the

Mississippi Valley lead and zinc regions, Freiberg in Germany, the Hauraki district of New Zealand, and many other places. Even in such regions, however, the intersections do not always have this effect, and it is the exception and not the rule to find it. Much more often they have no effect, and sometimes they have a bad effect, perhaps often because they may allow the leaching of some of the normal ore contents of the vein. When, however, the influence has been favorable, the result is often so very striking that this cause of ore-shoots must be considered one of the most important of all causes.[14] (See Fig. 3, 4, and 5.) Frequently cross-fissures

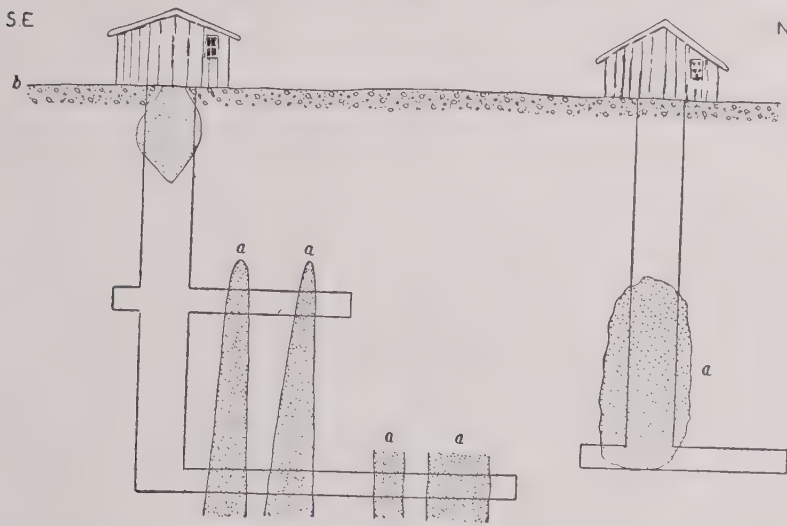

FIG. 5. Longitudinal section showing occurrence of ore-shoots in the Ida May mine, Cripple Creek, Colorado, after R. A. F. Penrose, Jr., 16th Ann. Rept., U. S. Geol. Survey, 1894-5, Pt. II.
a, a = ore-shoots; *b* = surface débris.
Scale, 1 inch = 50 feet.

intersect a vein after it has been formed, and may cause an enrichment of the original deposit by the influx of fresh ore-bearing solutions, just as in the case of veins fissured longitudinally by later breaks (see page 351).

INFLUENCE OF THE WALL ROCK OF FISSURES.

In many regions of fissure veins, the wall rock has a marked

[14] Where several parallel veins are intersected by a cross-fissure that has promoted deposition of ore, the shoots in each vein occupy a position in line with the cross-fissure, producing the effect known among miners as 'ore against ore.' (See page 325.)

effect on the quantity of ore present, and sometimes on the nature of the ore, thus greatly influencing the distribution of ore-shoots. A fissure intersecting different rocks may carry an abundance of ore in one rock and little or none in another, or may carry a certain ore in one rock and a different ore in another. These occurrences were once used by the strict lateral secretionists as arguments that the ore had been derived from the rocks immediately adjacent, and in some few cases, perhaps, this argument may have force, but in most cases the effect is probably due to the action of the wall rock, or the waters draining from it, on the ore-bearing solutions. The quantity of ore is the feature most generally influenced under these conditions, but some notable cases occur where different metals are found in different parts of a fissure, the change being coincident with a change in wall rock.

INFLUENCE OF THE PHYSICAL CHARACTER OF THE WALL ROCK OF FISSURES.

A given rock may be more open and porous than those associated with it, and if cut by a fissure, it may offer a better opportunity for the infiltration of ore-bearing solutions than the others, thus encouraging the formation of shoots. Moreover, a fissure intersecting different rocks often has a different character in one from that which it has in another. In one rock it may be a single, sharp, clean-cut break, in another it may fade out and disappear, in another it may be shattered and brecciated, and in still another it may separate into a number of more or less parallel fissures, forming a zone of fissuring; or many other forms may be developed, depending on the varying physical character of the different rocks. The more irregular and broken fissures offer better channels for percolating solutions than the clean-cut fissures with the two sides pressing close together, and, therefore, the rocks that produce the former conditions are frequently more apt to contain ore than the latter. On the other hand, if a fissure breaks up into a number of small fissures and the rock is not subject to replacement, the ore may sometimes be too much scattered to be of value.

Excellent examples of the change in the physical character of fissures as they pass from one rock to another, are seen at Cripple Creek, Colorado, where fissures are often well marked in certain rocks, while when they pass into more plastic materials they become much smaller or even disappear.[15] Somewhat similar cases are de-

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[15]Penrose, Jr., R. A. F. 'Mining Geology of the Cripple Creek District, Colorado,' 16th Ann. Rept. U. S. Geol. Surv., Pt. II, p. 144.

scribed by Irving and Emmons[16] in the Black Hills of South Dakota, by T. A. Rickard[17] at Rico in Colorado, by C. W. Purington[18] at Telluride, in Colorado, by J. E. Spurr[19] in the Mercur district of Utah, by R. Beck[20] near Freiberg, Germany, by De La Beche[21] in Cornwall, in England, by Von Cotta[22] at Przibram, in Bohemia.

INFLUENCE OF THE CHEMICAL CHARACTER OF THE WALL ROCK OF FISSURES.

General.—The chemical character of the wall rock of a fissure often has far more influence on the deposition of ore than the purely physical character, and frequently determines the existence or non-existence of ore in a fissure, thus influencing in a marked manner the distribution of ore-shoots. The rock in which a certain ore is abundant may have caused precipitation by a direct chemical effect on certain constituents of the ore-bearing solutions; or waters draining from this special rock and impregnated with the substance of it, or with other materials, may have had a similiar effect. The rock may also have been susceptible to replacement by certain materials in ore-bearing solutions, thus encouraging the concentration of ore by giving space for its accumulation. This replacement may have gone on by the removal of certain ingredients of the rock by the ore-bearing solutions and the substitution of certain other ingredients from the same solutions, practically simultaneously, and in this case the process represents that form of metamorphism known as metasomatism. In many cases, however, the replacement has gone on by the removal of certain ingredients of the rocks by one solution and the later substitution of other ingredients by the same or another solution. In this latter process, the change may progress particle by particle, in a very minute manner, or cavities of larger size may be formed, and even great cham-

16Irving, J. D., and Emmons, S. F. 'Economic Resources of the Northern Black Hills,' U. S. Geol. Surv., Prof. Paper, No. 26, Pt. II.

17Rickard, T. A. 'The Enterprise Mine, Rico, Colorado,' Trans. Amer. Inst. Min. Eng., Vol XXVI, pp. 976-977.

18Purington, C. W. 'Ore-Horizons in the Veins of the San Juan Mountains, Colorado,' *Economic Geology*, Vol. I, pp. 129-133.

19Spurr, J. E. 'Economic Geology of the Mercur Mining District, Utah,' 16th Ann. Rept. U. S. Geol. Surv., Pt. II, pp. 452-454.

20Beck, R. 'The Nature of Ore Deposits,' Weed's Translation, Vol. I, pp. 119-120.

21De La Beche, H. T. 'The Geological Observer' (Philadelphia, 1851), pp. 640-641.

22Von Cotta, B. 'A Treatise on Ore Deposits,' Prime's Translation, p. 48.

bers may result from the dissolving solutions and may later become the receptacles for ore.[23]

Limestone.—Many rocks have an influence on ore deposition, but some have much greater influence than others, and of all rock, limestone, including dolomite, has the most generally marked effect. Its influence is due both to the metasomatic replacement of calcium carbonate by materials from the ore-bearing solutions, and to the leaching out of cavities in the limestone and the substitution of other materials in the spaces thus formed. Its influence may perhaps sometimes be further increased when, under the action of certain solutions, the calcium carbonate is decomposed chemically, setting free carbonic acid, which may add greatly to the power of the solutions to dissolve limestone, thus increasing the number and

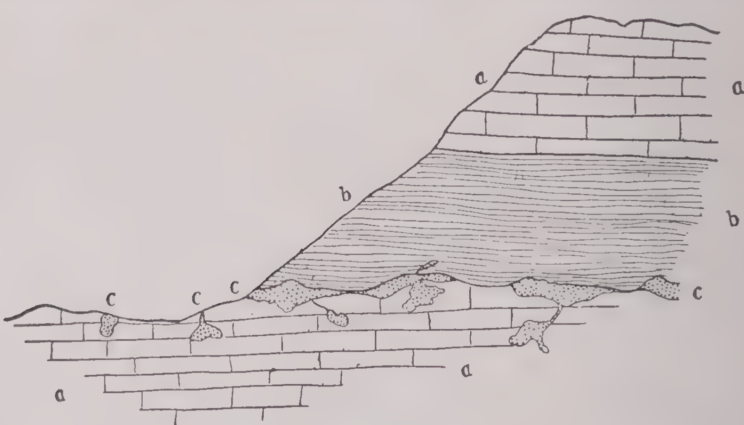

FIG. 6. Sketch section showing occurrence of ore-shoots in limestone at contact of overlying shale, at the Bremen mine near Silver City, New Mexico, by R. A. F. Penrose, Jr.
a, a = limestone; *b, b* = shale; *c, c, c,* = ore.

size of the cavities available as receptacles of ore. In a fissure crossing a series of interbedded limestones, sandstones, slates, etc., or limestones cut by igneous rocks, the preference of ore for the limestone rather than for the other rocks is often very marked, and large ore-shoots frequently occur where a fissure passes through this rock, while where it passes through other rocks the orebody may be much contracted. If a number of limestone strata separated by

[23] Where several parallel veins cross a formation that encourages ore deposition, the bodies of ore in each vein occupy a position in line with that formation, producing the effect known among miners as 'ore against ore.' (See page 325.)

other strata occur, a series of alternating wide places and narrow places may be found in the deposit. The ore-shoots in the limestone are often especially large at the contact of that rock with a less easily affected rock, a fact due probably to the slackening of speed and to the enforced accumulation of ore-bearing solutions at such places (see Fig. 6).

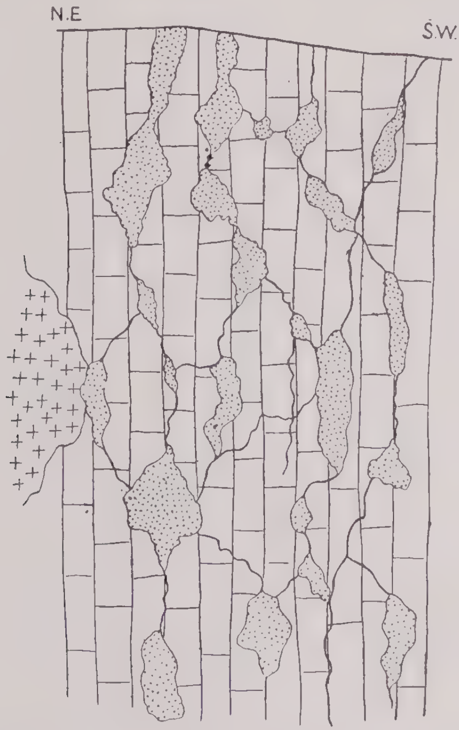

FIG. 7. Sketch section showing a typical occurrence of ore at Eureka, Utah, by R. A. F. Penrose, Jr.
Dotted parts indicate ore; the enclosing rock is limestone; on the left is an igneous mass.
Scale, 1 inch = 25 feet.

Examples of the influence of limestone on ore deposition are seen at many places in the world, especially in silver, lead, copper, iron, and sometimes gold and other deposits. Among such instances are Leadville and the San Juan region in Colorado; Bisbee, Clifton, Globe, and Tombstone, in Arizona; Silver City and Lake Valley in New Mexico; Park City and Eureka in Utah; Eureka in Nevada; Sierra Mojada in Mexico; various districts in British Columbia, and many other parts of North America. Similar occurrences are seen at Cumberland and Derbyshire in England, and many places in Chile and other parts of the world. Among the more common metals, many iron deposits are due to a replacement of limestone, as seen in some of the lower Paleozoic deposits in the Appalachian mountains, at the Calumet and the Orient mines in Colorado, at the Bilbao mines in Spain, at some of the mines of the Island of Elba, and many other places.

When limestone strata have been turned on end, and fissuring follows the strike, the formation may become so open and porous that large and extensive cavities are formed by the downward percolation of surface waters or the upward percolation of deep-seated waters, thus affording ready receptacles for ore-shoots. A remarkable instance of such leaching is seen at Eureka in the Tintic district of Utah, where a steeply dipping limestone is impregnated along its strike for a width of sometimes over 500 ft. with mineral matter (see Fig. 7). Many noted mines, such as the Eureka Hill, Bullion Beck, Gemini, Centennial, etc., are on this zone of mineralization. In one place on it, in 1894, there was in the underground workings an open natural chamber, formed by leaching, between 200 and 300 ft. long, 10 to 15 ft. wide, and over 100 ft. deep. This was formed after the deposition of ore, but similar chambers may have been formed before ore deposition, and later may have acted as receptacles for ore, in addition to the ore deposited by metasomatic replacement.

Though limestone has, more than any other rock, been instrumental in the formation of ore-shoots in various parts of the world, yet like most influences affecting shoots, its action is not universal, and there are many districts in which such rocks appear to have had no influence, while in some they appear to have been actually detrimental to the accumulation of ore. As a rule, however, unless limestone has been proved to have been inert or to have had a negative effect, it is always well to investigate its possible favorable influence on ore deposition.[24]

Siliceous Rocks.—Under the action of certain ore-bearing solutions, siliceous rocks may be extensively replaced, thus forming ore-shoots, though such results are not so generally marked as with calcareous rocks. At the principal silver-lead mines in the Coeur d'Alene district in Idaho, the ore deposits are mostly a replacement

[24]Any rocks containing calcium carbonate, like calcareous sandstone, calcareous shale, etc., tend to have an influence somewhat similar to limestone, on account of the ease with which ore-bearing solutions act on the calcium carbonate in them.

of quartzite and other siliceous rocks by siderite and argentiferous galena, with other minerals in small quantities.[25] Again in the iron districts of the Lake Superior region, Van Hise[26] has shown that many of the rich iron deposits were formed from low-grade ferruginous materials, and that this concentration progressed largely by the replacement of silica by iron ore. In this case the replacement has occurred on an enormous scale. In some cases certain silicates in crystalline rocks may be replaced more easily by ore than other silicates or other constituents of the rock, thus influencing shoots in certain rocks containing the replaceable materials.[27]

Organic Matter.—When a vein crosses a formation highly impregnated with organic matter, ore-shoots often occur, and this is probably due to the action of the organic matter on ore-bearing solutions, causing precipitation by its reducing action or by other chemical means. Such occurrences are seen in some of the lead and zinc regions of the Upper Mississippi[28] and of Missouri,[29] at Bingham,[30] in Utah, and in parts of the Mother Lode region of California. In northern New Mexico,[31] wood, branches of trees, and leaves are found converted to copper minerals, showing the effect of vegetable matter on copper-bearing solutions, and similar occurrences are seen in northern Texas,[32] as well as in many other places in America and Europe. At Freiberg[33] in Germany, veins crossing graphitic schist are richer than elsewhere, and at Mansfeld[34] in Germany the copper ores are notably rich in bituminous formations. Organic matter is supposed to have had marked effect on ore deposition at Ballarat, Victoria, where a very thin but quite

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[25]Ransome, F. L., and Calkins, F. C. 'The Geology and Ore Deposits of the Coeur d'Alene District, Idaho,' U. S. Geol. Surv., Prof. Paper No. 62.

[26]Van Hise, C. R. 'The Iron Ore Deposits of the Lake Superior Region,' 21st Ann. Rept. U. S. Geol. Surv., Pt. III, pp. 305-434.

[27]See W. H. Weed, 'Influence of Country Rock on Mineral Veins,' Trans. Amer. Inst. Min. Eng., Vol. XXXI, pp. 634-653. Also, 'Geology of the Little Belt Mountains, Montana,' 20th Ann. Rept. U. S. Geol. Surv, Pt. III, pp. 418-420.

[28]Chamberlin, T. C. 'Geology of Wisconsin,' Vol. IV, pp. 547-549. Blake, Wm. P. 'The Lead and Zinc Deposits of the Mississippi Valley,' Trans. Amer. Inst. Min. Eng., Vol. XXII, pp. 630-631.

[29]Jenney, W. P. 'The Chemistry of Ore Deposition,' Trans. Amer. Inst. Min. Eng., Vol. XXXIII, pp. 445-498.

[30]Boutwell, J. M. 'Genesis of the Ore Deposits at Bingham, Utah,' Trans. Amer. Inst. Min. Eng., Vol. XXXVI, pp. 541-580.

[31]Cazin, F. M. F. *Eng. & Min. Jour.*, Vol. XXX, p. 381.

[32]Schmitz, E. J. 'Copper Ores in the Permian of Texas,' Trans. Amer. Inst. Min. Eng., Vol XXVI, pp. 97-108.

[33]Von Cotta, B. 'A Treatise on Ore Deposits,' Prime's Translation, pp 46-47.

[34]Von Cotta, B. *Op. Cit.*, p. 166.

persistent stratum of black slate appears to have caused an increase in ore where veins cross it, and hence is locally known as the 'indicator'.[35] A similar influence of organic matter is seen at Bendigo in Victoria and at Gympie in Queensland.

Sulphides.—Any rocks heavily charged with iron pyrites or other sulphides may have an effect on ore-bearing solutions on account of the precipitating action of the sulphides. This action is analogous to that of sulphides in veins on later ore-bearing solutions, and is further discussed on pages 349 and 351.

Igneous Rocks.—Many ore deposits in regions of igneous rocks are directly due to the various influences of subsiding igneous activity; but there is a class of ore deposits, and of ore shoots in these deposits, which has been caused simply by the chemical and physical action of certain mineral constituents in igneous rocks on ore-bearing solutions, in a manner analogous to the way certain sedimentary rocks, already described, affect such solutions. Thus in the Lake Superior copper region, the copper occurs with basic volcanic rocks and is supposed to have been precipitated by the action of ferrous compounds in these rocks on copper-bearing solutions.[36] Frequently the copper has more or less replaced the country rock, especially in some of the volcanic conglomerates, in which the open structure allowed a free percolation of metalliferous solutions. In the San Juan region of Colorado, according to C. W. Purington, the ore in different strata of andesitic breccia is more abundant in those strata which carry large quantities of basic minerals than in other strata.[37] These processes of replacement in igneous rocks are often greatly hastened where more or less of the original heat and other accompanying phenomena of subsiding igneous activity still remain. Such may have been the case at the time of deposition of some of the ore at Cripple Creek, Colorado, where an andesitic breccia and sometimes other igneous rocks, have been extensively replaced, often forming large orebodies in the wall rock

[35]Rickard, T. A. 'The Indicator Vein, Ballarat, Australia,' Trans. Amer. Inst. Min. Eng., Vol. XXX, p. 1004-1019. The 'Indicator' also contains large quantities of iron pyrites, and some authorities claim that the influence of the 'Indicator' was due to the action of this on the ore-bearing solutions and not to the action of the carbonaceous matter; but Mr. Rickard believes that the carbonaceous matter caused the deposition of the iron sulphide, and that, therefore, it has been either directly or indirectly, the cause of the increase of ore in the veins crossing it.

[36]Pumpelly, R. 'Geology of Michigan,' Vol. I, Pt. III, p. 43. Irving, R. D. 'The Copper-Bearing Rocks of Lake Superior,' Mon. U. S. Geol. Surv., No. 5, pp. 420, 425-426.

[37]Purington, C. W. 'Ore Horizons in the Veins of the San Juan Mountains, Colorado,' *Economic Geology,* Vol. I, p. 133.

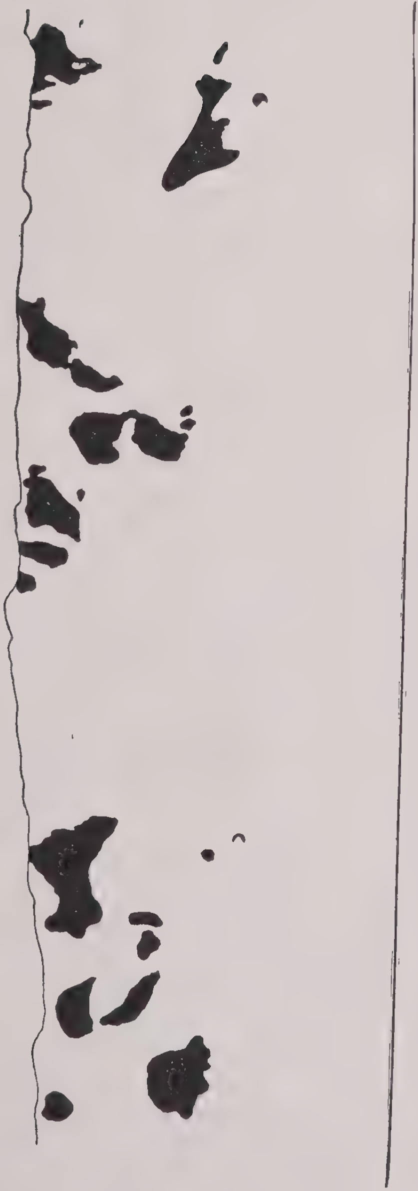

FIG. 8. Longitudinal section through some of the principal mines of the Comstock Lode, Nevada, showing the distribution of ore-shoots. Compiled by writer from data in the atlas accompanying Monograph III of U. S. Geol. Survey, by George F. Becker. The black markings indicate ore. Scale, 1 inch = about 1730 feet.

along very narrow fissures.[38] Again, in the tin deposits of Mount Bischoff, Tasmania, extensive replacement of an igneous rock, probably under conditions of heat, has taken place. The ore occurs not only in fissure deposits, but also extensively as replacement of quartz-porphyry.[39] At the time of my visit to this mine in 1904, large quantities of the igneous rock partly replaced by cassiterite were being mined as ore. Many other similar cases of extensive replacement of igneous rocks under conditions of heat might be mentioned.

Contact Deposits.—The subject of the increased chemical activity of underground waters near igneous rocks, leads up to that large and important class of orebodies known as contact deposits, lying at or near the contact of the country rock with dikes or other igneous masses. This subject, however, involves more the study of the varied effects of hot igneous rocks on the general geological and chemical conditions of the region, than the direct action of a rock on the character or quantity of ore within it, and though of great scientific and industrial importance, it is beyond the scope of this paper. Suffice it to say here that the occurrence of contact deposits near igneous rocks is probably due in most cases to the fact that the latter are manifestations of past igneous activity, and ore-bearing solutions are generally recognized as being especially abundant and active under such conditions; while in some cases the presence of the ore may be due to a source from the igneous rocks, or to the adjoining presence of an easily replaceable rock, or to the fact that the intrusion of the dike has caused fissuring favorable for ore deposition, or to all these causes combined and many others. Such deposits are so numerous as hardly to require illustrations, but it may be said that the silver mines of Leadville and many of the copper mines of Globe, Clifton, and Bisbee in Arizona, the copper mines of Rio Tinto in Spain, and many great mines elsewhere represent contact deposits.

Different Ores in Different Rocks.—The influence of the wall rock on fissures and shoots, already described, relates largely to the effect on the quantity, rather than on the nature of the ore. In some places, however, the nature of the ore is affected, and a fissure passing through different rocks may contain one ore where

[38]Penrose, Jr., R. A. F. 'The Mining Geology of the Cripple Creek District, Colorado,' 16th Ann. Rept. U. S. Geol. Surv., Pt. II, 1894-5. Also, Lindgren, W., and Ransome, F. L. 'Geology of the Gold Deposits of the Cripple Creek District, Colorado,' U. S. Geol. Surv., Prof. Paper No. 54, 1906.

[39]Von Fircks, W. *Zeit. der deuts. geol. Gesell.*, 1899.

it intersects one rock and another ore where it intersects another rock.

At the Dolcoath mine in Cornwall, England, the orebody was rich in copper near the surface, where it intersected slate, and rich in tin lower down, where it intersected granite. At the time of my visit to this region in 1901, the mining for copper had long ceased, but tin was being actively produced from a depth of over 3000 ft. The ore of the mine had been copper down to depths ranging from 850 to 1150 ft., which approximately represented the depth of the slate and granite contact. Below, tin became mixed with the copper, and both metals were contained in the ore for a further depth of from 200 to 250 ft., when the copper gradually disappeared and tin became the only important metal. At Klausen in Austrian Tyrol, the veins are rich in silver, lead, and zinc where they intersect slates and diorites, and rich in copper where they intersect mica schist and felsite; in the Salzberg Alps some of the veins contain gold where they intersect gneiss, and silver where they intersect limestone.[40] In Montgomery and Chester counties, Pennsylvania, where the Triassic sandstone comes in contact with gneiss, copper often occurs in the former rock and lead in the latter.[41]

This influence of country rock on the nature of the ore in a fissure, however, is the rare exception and not the rule. The effect is much more frequently noticeable on the quantity of ore. Moreover an apparent, but deceptive, relation of the nature of the ore to country rock may sometimes be due to the fact that, in solutions rising in a fissure, as the pressure and heat diminish, certain ores may be deposited at a certain depth and others at another depth, according to the conditions of pressure and temperature that permit the precipitation of each.[42] If in this process a certain ore should happen to be deposited where the fissure intersects one rock and another ore where it intersects another rock, the impression might be given that the different rocks had caused the deposition of different ores, whereas the result had been brought about by other influences.

INFLUENCE OF SUPERFICIAL AND DEEP-SEATED ALTERATIONS.

Constant Changes in Ore Deposits.—An ore deposit is never in a

[40] Von Cotta, B. 'A Treatise on Ore Deposits,' Prime's Translation, p. 48.

[41] Rogers, H. D., and Genth, F. A., quoted by J. D. Whitney. 'Metallic Wealth of the United States,' pp. 328, 396-398.

[42] A lowering of temperature due to local causes and not necessarily to an approach to the surface, may also have a similar effect in promoting deposition.

state of complete chemical stability. Even before it is formed, the fissure or other position which it later occupies, is the scene of constant changes as a result of the reactions of different solutions on each other. These reactions ultimately result in the deposition of ore, but no sooner is it formed than surface influences, and often deep-seated influences, begin to alter its chemical and physical condition.

Many ore deposits have been derived from hot solutions, often near hot igneous rocks, and after their formation there is a tendency to cool off, a process which may cause them to shrink and become cracked. Moreover, a fissure is a line of weakness, and the movement that produced it may be repeated frequently along its course, even after an ore deposit has been formed in it. This is especially true where the fissure has been partly filled with ore, the rest being more or less filled with selvage. The later fissuring may occur many times in the geological history of an ore deposit and often causes considerable crushing and brecciation in it. Transverse fissuring may also still further shatter the deposit. These conditions tend to allow surface waters to percolate into the deposit from above, and sometimes subterranean waters to act from below. Moreover, orogenic movements may elevate the region and stimulate erosion, thus exposing new parts of the deposit to surface alteration; or similiar movements may depress the region and subject the deposit to renewed attacks by deep-seated solutions; fresh movements along the fissure may cause renewed shattering; while climatic changes may alter the character of the surface agencies and give renewed strength to their chemical activity. Thus the influences to which a deposit is exposed are constantly changing, and no sooner does it show a tendency to chemical stability, than new conditions start fresh chemical activities; and it cannot be said that the formation of an ore deposit is ever completed. From the time its formation begins to the time the miner carries away the ore, the deposit is being changed by natural agencies both from above and below. The result is often the formation of ore-shoots in places where they did not exist before; or the modification of pre-existing ore-shoots either by accretion or diminution of mineral contents. The processes involved in these changes are often similiar to those already described in this paper, in other cases they are somewhat different.

Superficial Alteration.—In considering the superficial alteration of ore deposits, a subject analogous to the surface decay of rocks is discussed. The latter, however, involves but a limited number of rock-forming minerals, while the superficial decay of ore deposits involves a great variety of minerals, many of which, under surface influences, give rise to intricate chemical changes. These alterations are the result of the combined action of the atmosphere, surface waters, changes in temperature, and the various organic and inorganic materials contained in the air and water. In nature perfectly pure water does not occur, but different waters contain different ingredients derived from the air and from other materials with which they come in contact. Among the most important of these ingredients are oxygen and carbonic acid, together with numerous other acids, both organic and inorganic, either in a free state or combined with bases. Surface waters, thus charged with various chemical ingredients, percolate down into ore deposits and cause great changes in their physical and chemical condition. The oxidation and hydration of certain ingredients, the formation of other new chemical combinations, the leaching of certain ingredients and their deposition below, or their removal altogether from the deposits, and many other effects, are produced. As a result, certain metalliferous ingredients are sometimes leached from the upper parts of ore deposits and carried down into lower parts, where they are re-precipitated by meeting other solutions, or by meeting rocks or minerals which cause deposition, such as calcareous and carbonaceous rocks, masses of sulphides, etc. Hence rich bodies of ore in the form of shoots often collect between the overlying altered part of a deposit and the underlying unaltered part. Such shoots, by their very mode of formation, often tend to have an oblong form, running in the direction of the strike of the vein rather than, as with most other shoots, running downward in it. On their lower side, they often extend out in long projections or tongues, tapering downward until they disappear. The miner's term 'fingering out' well expresses this condition.

Ore-shoots may be formed higher up in the altered parts of a deposit in cases where certain materials are more resistant to leaching than others, a condition resulting in the concentration *in situ* of the former by the removal of the latter. Thus in an orebody containing copper and gold, surface agencies may leach the copper and deposit it below, forming a copper ore-shoot, while the gold being less affected remains above, and may develop into a richer deposit than originally, by the removal of the copper and other soluble materials. In the same way the leaching of certain gangue minerals, like calcite, may cause a concentration of certain metalliferous materials that offer more resistance to leaching.

The depth to which superficial alteration may go is influenced by the topography, the rapidity of erosion, the climate, and many other causes, and ranges from a few inches to many hundred feet, perhaps in some cases to several thousand feet. Though most of the ore-shoots due to this cause are more or less superficial, yet they are often of immense commercial importance, both in deposits of the precious and base metals. Many of the great ore-shoots of the Comstock lode in Nevada, of the Butte region of Montana, of the arid regions of Utah, Arizona, and New Mexico, many of the iron deposits of Michigan, Wisconsin, and Minnesota, and in fact many of the greatest orebodies of the world, owe their existence, in part at least, to this superficial alteration. As in other influences affecting ore-shoots, however, superficial alteration is not always favorable, and frequently it has an impoverishing effect, but when it enriches the deposit, the results are often wonderfully great.[43]

The mines of Butte, Montana, were originally started as silver mines, but at a depth of a few hundred feet, copper minerals appeared with the silver, and eventually were found in such enormous quantities as to form the basis of one of the greatest copper-mining industries in the world. In this case the ore originally contained copper and silver, but the copper was leached from above, leaving the less soluble silver minerals, and was carried down into the lower parts of the deposits where it enriched the original ore. In a similar manner, at the great Mount Morgan mine in Australia, the ore near the surface was rich in gold, but carried only insignificant quantities of copper. Lower down, however, copper became abundant, and the mine is now a producer of both metals. At the time of my visit to this mine, in 1904, it had reached a depth of over 800 ft., and works were just being erected to treat the vast quan-

[43]This subject of the superficial alteration of ore deposits is too large to be more than thus briefly mentioned in this general paper, but for its further discussion the reader is referred to: 'The Superficial Alteration of Ore Deposits,' by R. A. F. Penrose, Jr., *Jour. Geol.* Vol. II, 1894, pp. 288-317. 'The Secondary Enrichment of Ore Deposits,' by S. F. Emmons, Trans. Amer. Inst. Min. Eng., Vol. XXX, 1901, pp. 177-217. 'The Enrichment of Gold and Silver Veins,' by W. H. Weed, Trans. Amer. Inst. Min. Eng., Vol. XXX, 1901, pp. 424-448. 'The Iron Ore Deposits of the Lake Superior Region,' by C. R. Van Hise, 21st Ann. Rept. U. S. Geol. Surv., 1901, Pt. III, pp. 305-434. 'The Formation of Bonanzas in the Upper Portions of Gold Veins,' by T. A. Rickard, Trans. Amer. Inst. Min. Eng., Vol. XXXI, 1901, pp. 198-220. 'Ore-Deposition and Vein Enrichment by Ascending Hot Waters,' by W. H. Weed, Trans. Amer. Inst. Min. Eng., Vol. XXXIII, 1903, pp. 747-754. 'Secondary Enrichment in Ore Deposits of Copper,' J. F. Kemp, *Economic Geology,* Vol. I, 1905, pp. 11-25.

tities of copper that had been found. In this case the copper had been mostly leached from the upper parts of the deposit and the gold left as a concentrated residual product, forming ore often of fabulous richness. Lower down, when the copper appeared, the gold still remained, but not having been concentrated by the leaching of other materials, the ore was less rich in it. The manganese deposits of the Batesville region of Arkansas are excellent examples of the concentration of ore as a residual product. Here the ore was once disseminated in limestone, and where surface waters have leached this rock, the less soluble manganese ore has collected in rich pockets in the residual clay left by the limestone.[44]

Deep-Seated Alteration.—While superficial influences are altering the upper parts of an ore deposit, deep-seated influences may also be active below. The repeated longitudinal fissuring of a deposit after its formation, as explained on page 348, may afford new channels for the circulation of new ore-bearing solutions from below, and these may profoundly affect the deposit. They may form new ore in new openings, or add to the ore already existing, or perhaps segregate ore formerly disseminated, in all of which cases ore-shoots may result. Where large bodies of sulphide ores existed in the original deposit, these may be greatly increased by their precipitating action on the new ore-bearing solutions. The new solutions may sometimes contain different metalliferous materials than the older solutions that formed the original deposit, and may thus form new shoots of different ore. Where an orebody has been intersected transversely by later fissuring, effects somewhat similar to those just described as following later longitudinal fissuring may result, but here the action is confined largely to the point of intersection, instead of being spread along the whole fissure, as in longitudinal fissuring.

In all these processes, however, the result is not always an increase of value or volume of ore, and, as with most factors which influence ore-shoots, there may be no effect at all, or there may be an actual diminution of ore. For instance, when the longitudinal movement along a fissure occurs at only more or less remote intervals of time, deposition of ore may be increased as just described, but when the movement is very frequent or almost continuous, it is likely to retard deposition or even to prevent it, for deposition progresses best during intervals of repose after dynamic movements. This

[44]Penrose, Jr., R. A. F. 'Manganese: Its Uses, Ores, and Occurrence,' Geol. Surv. Arkansas, Vol. I, 1890, pp. 174-177.

may be a cause of the fact observed in some mining regions, though by no means in all, that the ore deposits occur in the smaller fissures, and not in those that have been the scenes of the greatest amount of movement.

An excellent case of enrichment from below as the result of repeated movements along ore-bearing fissures, is seen at Goldfield, Nevada, where some of the deposits have been shattered by longitudinal fissuring many times and have received new supplies of ore at different periods.[45] Remarkable cases of enrichment after later fissuring, both longitudinal and transverse, are also seen at Butte, Montana, and other districts.

SUMMARY.

Ore-shoots are bodies of mineral matter richer in certain valuable constituents than the enclosing materials. They may be of varying size, continuity, and shape, but their more or less circumscribed character is a distinguishing feature.

Ore-shoots are the result of many different chemical and physical influences. These influences sometimes act singly, but generally two or more, often many, act together in producing a given shoot.

Segregation during the cooling of molten magmas in some cases influences the formation of ore-shoots.

The occurrence of ore-bearing solutions in local vents influences the position of ore-shoots by supplying materials for them in some places and not in others. Thus the channels of fumaroles and hot springs may become the receptacles for shoots.

Gaseous emanations may influence the position of ore-shoots by causing precipitation where they occur or by forcing ore-bearing solutions along certain channels.

Structural conditions in a fissure may influence the deposition of ore-shoots by offering advantageous openings for deposition, by forcing the ore-bearing solutions into favorable position for deposition, and in other ways.

Cross-fissures may influence the deposition of ore-shoots by supplying an additional amount of ore-bearing solution, by shattering the wall rock at the point of intersection, by supplying solutions which cause precipitation from the solutions in the main fissure, by deflecting the solutions in the main fissure to advantageous positions for deposition, and in other ways.

The nature of the wall rock of a fissure may influence the depo-

[45]Ransome, F. L. 'The Mining Geology of Goldfield, Nevada,' U. S. Geol. Surv. Prof. Paper No. 66, pp. 196-198.

sition of ore-shoots to a very marked extent. Its influence is chiefly in affecting the quantity of the ore, but it may also affect the nature of the ore. Its influence is both physical, in affording the places for deposition, and chemical, in causing precipitation of ore.

The superficial and deep-seated alterations of an ore deposit after its formation, may greatly influence the distribution of ore-shoots by the chemical and physical changes that they produce, forming shoots where they did not exist before, or modifying pre-existing shoots either by accretion or diminution of mineral contents.

CONCLUSION.

Many causes tending to produce ore-shoots have been mentioned, and their action might have been discussed at greater length, but any attempt to follow all the modifications and combinations of the processes described would involve too much detail for a general paper. Probably the most important and generally observed influences producing ore-shoots are those of the wall rock, of intersecting fissures, and of local emanations of ore-bearing solutions. These influences, however, rarely act singly; they generally combine with each other or with still different influences in producing ore-shoots. As has been frequently stated before in this paper, however, the influences that may produce ore-shoots do not necessarily do so. An ore-shoot is the exception and not the rule, and even when apparently the most favorable combination of influences exists, there may be no ore-shoot. Moreover, the causes that have produced a shoot in one region may have no such effect in another region, or in another ore deposit in the same region, or perhaps in another place in the same ore deposit. In one place, the wide spots in a vein may be the most likely for shoots; in others, the wide spots may be barren and the narrow places rich; in one place, shoots may have a close connection with cross-fissures, in another such fissures may be entirely without influence; in one place, shoots may show a decided preference for certain rocks, in another the same rocks may seem to discourage shoots. In some places, the action of surface influences, causing a superficial enrichment, has been a most important factor in developing ore-shoots, in others it has either had no influence or may even have deteriorated the value of shoots that existed before its influence was felt; in some places, later movements along a fissure that has already been filled with ore have had a marked enriching effect, in others such movements have had no effect.

More financially disastrous mistakes have probably been made in mining by supposing that because certain conditions hold good in one region, they must hold good in another, than from any other one cause. Every district is a law unto itself in the localization of its ore in shoots, and no district can be properly understood until it has been thoroughly studied *per se*. On the other hand, shoots are not one of those obscure and mysterious phenomena which baffle all efforts at explanation. They are simply the result of natural causes which have been, and are sometimes even yet, active. In almost any district where sufficient mining has been done to permit a thorough examination of the ore deposits, some sort of an idea of the probable cause of the ore-shoots should be obtainable. Though the occurrence of an ore-shoot, even under conditions most favorable for its formation, is the exception and not the rule, yet it is worth while to study the causes that produced it, and to look for ore under similar conditions elsewhere. The search in many cases will be fruitless, but another 'exception' exists somewhere, and a knowledge of the conditions under which it may occur is helpful. Just as the pearl in the oyster is an abnormal segregation resulting in a beautiful gem, so the ore-shoot in the earth is an abnormal segregation resulting in precious minerals; just as there are thousands of oysters that contain no pearls to one that does, so there are thousands of apparently favorable receptacles for ore-shoots that yet carry none; just as the pearl diver finds it remunerative to hunt for the oyster that may contain his prize, so the miner finds it remunerative to hunt for the spot that may contain his ore-shoot; and though the paths of both are strewn with disappointed hopes, yet the possibility of realization leads them on.

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